

# REPORT DOCUMENTATION PAGE

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Please find attached the slide report for the Nanosat program with the Emerald satellite, This is for the combined efforts of the Stanford and Santa Clara University Emerald Project.					
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# *Nanosat One Critical Design Review*

Principal Investigators:

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Prof. Christopher Kitts

Prof. Robert Twiggs

## University Schedule

Emerald structures, mechanisms, and thermal Systems

- Program introduction
- Emerald/Orion common systems
- Emerald specific systems/experiments
- Orion specific systems/experiments

## University Program Overview

- 3 satellites organized in 2 missions
- Orion Project
  - Stanford University
  - MIT
- Emerald Nanosatellite Project
  - Stanford University
  - Santa Clara University

## Three Satellite Mission

- Formation Flying Concept
- Mission Description
- Mission Objectives
- Mission Profile
- Project Schedule

## Formation Flying Concept

The small satellite advantage!

- Less costly
- Simpler designs
- New mission architectures

Clusters of cooperative satellites

Applications

- Synthetic apertures
- Distributed field measurements

Support from NASA & USAF

## Formation Flying Concept

Challenges:

- Limited mission resources
- Fleet management & control
- Communication architecture

Methodology

Basic research    Testbed missions

Verify principles    Validate design concepts

## Mission Description

Demonstrate closed-loop formation flying in space

Carrier phase GPS data shared  
(Allows relative navigation & formation flying)

Emerald 1 (Beryl)

- Two GPS antennas
- One GPS receiver
- Limited control

Orion

- Six GPS antennas
- Three GPS receivers
- Full 6 DOF control

Emerald 2 (Chromium)

**MISSION OBJECTIVES**

Comprehensive on-orbit demo of *true formation flying*

- Develop technologies to build a *virtual spacecraft bus*
- GPS sensing & fleet control

Orion-Emerald system is a *flexible, low-cost* test platform

Leader-referenced control      Centralized control

**MISSION PROFILE**

Shuttle Launcher

Start-up operations

Emeralds separate

Nominal operation

Emerald 1 (Beryl)

Emerald 2 (Chromium)

Orion

Timeline:

- $t = 0$ 
  - MSDS ejected
  - Orion-Emeralds on MSDS
  - ALL systems UN-powered
  - Power inhibits unmonitored
- $t = t_1$  (20 min)
  - Orion-Emeralds on MSDS
  - MSDS signal #1 activated
  - First set of inhibits closed
  - Safety-Critical Systems UN-powered
- $t = t_1 + t_2$  (20 min + 4 days)
  - MSDS signal #2 activated
  - Second set of inhibits closed
  - ALL systems powered
  - Orion & Emeralds deployed

**PROJECT SCHEDULE**

2000			2001				2002
Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1
Engineering Model			Flight Hardware				
			Testing & Operations				
			Deliver to AFRL				
			Deliver to GNE				
			Launch				

**ORION OVERVIEW**

- Development Team
- Mission/Experiments
- System Summary
- Requirements

**ORION DEVELOPMENT TEAM**

- Space Systems Development Lab
  - Dept. of Aeronautics and Astronautics, Stanford University
- Space Systems Laboratory
  - Dept. of Aeronautics and Astronautics, MIT

<http://ssdl.stanford.edu/orion>

**ORION MISSION**

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Emerald 2 (Chromium)

Orion

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- Three GPS receivers
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**Experiments**

**PHASE 1:** Orion in formation with 1 Emerald

- Emerald only performs GPS data collection & comm link
- Orion performs closed-loop control w.r.t. Emerald
- Various (in-track) coarse, fine-parking, & precision modes
- At least 3 orbits, & repeatable over 2 weeks

**PHASE 2:** Orion in formation with 1 Emerald

- Emerald provides GPS data/comm link
- Emerald also responds to control inputs from Orion
- At least 3 orbits, & repeatable over 2 weeks

**PHASE 3:** Orion in formation with both Emeralds

- Same as phase 2, apply various control architectures
- At least 3 orbits, repeatable

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**Operational Details**

- Align Emerald in-track positions as closely as possible
- Orion in closed-form relative motion with respect to the Emeralds' mean formation geometric center.
- Emeralds provide GPS data/comm link & respond to control inputs from Orion

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**System Concept**

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**Orion Design Requirements**

- Technical Goals
- Performance Requirements
- Safety Summary
- Integration

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**Technical Goals**

- Demonstrate control for a cluster of micro-satellites.
  - real-time autonomous control software
  - formation directed at a high-level from the ground.
- Demonstrate GPS receiver for real-time attitude & relative navigation
  - first on-orbit demonstration of CDGPS for precise relative navigation and control
  - Expect  $< 1$  m (relative - radial) for determination & 5 m (relative - radial) for control.
  - low-power, low-cost, attitude capable GPS receiver.
- Various control architectures and a real-time inter-vehicle communication link and ranging.

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**Performance Requirements**

**Mission success:**

• Relative position determination	~10 cm
• Relative position control	~5 m
• Attitude determination	~2°
• Attitude control	~10°

**Key design requirements:**

- GPS receiver must function properly at all times
- Communications design must allow for direct data exchange between satellites during all phases
- Flight control software must control the constellation to the required degree of accuracy
- System resources must be sufficient to perform experiments as needed

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## Performance Requirements

General bus requirements:

- Mass and size restrictions as defined by MSDS budgets
- Components must operate within expected thermal environment
- Components must operate within expected radiation environment
- Component-level size, mass, and power restrictions

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## Performance Requirements

Subsystem requirement summary:

### Structure

- Provide structural support & mounting surfaces for all subsystem components
- Total system mass < 40 kg
- Structural fundamental frequency > 100 Hz
- Center of mass location within 1/4" radius of geometric z-axis
- Survive launch loads
- Minimize changes to inertia matrix over time
- Fracture controls

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## Performance Requirements

### GPS Payload

- Acquire and maintain GPS signal lock in all flight modes
- Sense satellite state (absolute & relative) to required mission levels
- Calculate satellite state at a sufficient rate to achieve necessary control bandwidth
- Calculate control responses at a sufficient rate

### Power

- Supply enough current at appropriate voltage for all flight modes

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## Performance Requirements

### Attitude Determination & Control

- Provide enough actuation authority for all flight modes in all expected environmental conditions
- Robustness against failure or poor performance
- Enough resources to ensure minimum mission success

### Communications

- Provide reliable downlink and crosslink
- Utilize low-cost (amateur) transmission frequencies

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## Performance Requirements

### Command & Data Handling

- Provide enough memory and processing speed to handle housekeeping tasks and routine data collection
- Provide serial interfaces to communications and GPS subsystems
- Provide PIC interface to ADCS and telemetry for distributed computing efficiency

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## Safety Summary - Structure

Issue	Hazard	Control
Strength	Structural failure due to insufficient design	Sine Burst Testing, FEM modeling
Natural Frequency	Dynamic coupling	Model Testing, FEM Modeling
Acoustic	Structural failure during launch	Random Vibration Testing
Envelope	Interference with other payloads, ground support equipment etc.	Approved envelope compliance
Fracture Control	Structural failure due to flaws	Approved critical components and compliances
Manufacturing	Structural failure due to poor quality	Engineering Model, manufacture by procedure

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**SDS** **SSDL**

## Safety Summary - Propulsion

Issue	Hazard	Control
Components leak or rupture	Explosion, venting	Components meet/exceed required FOS Components tested to 1.5 x MDP System tested to 1.2 x MDP
Operational inhibits (Mechanical)	Inadvertent operations & associated hazards	2 fault tolerant design to prevent inadvertent venting of gas
Operational inhibits (Electrical)	Inadvertent operations & associated hazards	Latching relay inhibits on all subsystems with catastrophic hazards (x4)

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**SDS** **SSDL**

## Safety Summary - Power

Issue	Hazard	Control
Battery containment	Shorting, insecure positioning	Sealed T6061 Aluminum box
Battery leak or rupture	Fire, explosion, contamination, corrosion	Pressure relief valves with inline filters (20 psi crack pressure), (x2) Fiberglass absorbing material
Battery charging inhibits*	Overcharging hazards	Latching relay inhibits on solar cell-battery circuit path (x4)
Operational inhibits*	Inadvertent operations & associated hazards	Latching relay inhibits on all subsystems with catastrophic hazards (x4)

\* Power inhibits are disabled when Orion receives a "safe distance" signal from the MSDS

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**SDS** **SSDL**

## Safety Summary - Torquer Coils

Issue	Hazard	Control
None	n/a	n/a

- No critical hazards exist
- Coil system is power inhibited with rest of main bus
- For inadvertent operation, analysis shows compliance with ICD 2-19001 section 10.7.3.2.1.2

Verification

- Measure the generated field strengths on flight article

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**SDS** **SSDL**

## Safety Summary

**Comm**

Issue	Hazard	Control
Inadvertent transmissions	Interference with Shuttle electronics	3-fault tolerant power inhibit scheme

**CDH**

Issue	Hazard	Control
Inadvertent operation of subsystems	Operation of hazardous subsystems	<ul style="list-style-type: none"> <li>3-fault tolerant power inhibit scheme</li> <li>Critical functions require confirmation</li> <li>I2C commands require checksum</li> </ul>

• Refer to: SSP for details on the attitude control system and power system  
• EMI is being tested on the system

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**SDS** **SSDL**

## Integration Requirements

### MSDS Integration

- Satellite must interface with MSDS deployment mechanism
- Satellite and all protrusions must fit within MSDS stack envelope

### Ground Operations

- External port for battery charging
- Inhibit verification
- Operational testing
- Other servicing requirements

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**SDS** **SSDL**

## Emerald Overview

- Development Team
- Mission/Experiments
- System Summary
- Requirements

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## Development Team

- Stanford University
  - Graduate and undergraduate students
  - Master's and Ph.D. level
  - Volunteer time, work for course credit, Research Assistantships
- Santa Clara University
  - Undergraduate seniors
  - Senior design project credit
- <http://ssdl.stanford.edu/emerald>

## Emerald Mission

### Demonstrate Robust Distributed Space Systems

- A distributed architecture to facilitate integration and operations.
- Distributed and autonomous science experimentation and satellite operation
- Supporting subsystem-level technologies
- Simple closed-loop relative position control for 2 and 3 bodies (with Orion)
- Low-cost satellite development techniques

## Development Approach

- Rapid prototyping: off-the-shelf components
- Building-block strategy
  - Start with minimized baseline design
  - Add features as time and funding allow
- Industry guidance and support
  - Mentors
  - Partnerships
- Aggressive schedule
- Internet distribution of information

## Emerald Experiments




- GPS Formation Flying
- VLF Atmospheric Science
- Colloid Micro-Thruster
- Radiation Test Bed
- Experimental C&DH architecture

## System Summary

- 19" hex, 9" x 12" sides
- Al honeycomb, stackable trays
- 12 v and 5 v reg. power
- I<sup>2</sup>C data & command bus
- Dallas 1-Wire power switching & telemetry
- Half-duplex inter-satellite communication
- Full-duplex ground link
- Drag panel position control
- GPS relative positioning



## Sources of Requirements




- Mission fulfillment
  - Experiment success
  - Operational integrity
- AFRL – for MSDS integration
- Launch safety considerations

## Requirements Outline



- Emerald Stack
- Subsystems
  - EPS
  - STRUCT/MECH
  - ADCS
  - COMM
  - CDH
- Experiments
  - VLF
  - CMT
  - MERIT
  - Formation Flying







## Stack Requirements

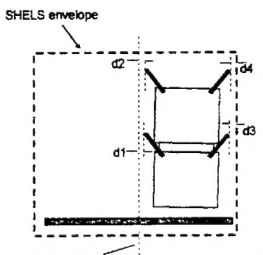
- Mission success
  - Groundlink communication while stacked
  - Commandable separation
- AFRL integration
  - Envelope restrictions (RFDW)
  - < 50 kg
  - Natural frequency > 100 Hz













## RFDW for Envelope Req.

- Comm antennas extend beyond AFRL envelope
- All clearances greater than .3 in. for SHELS static envelope











## EPS Requirements



- Mission Success
  - Provide sufficient regulated power to nanosat systems throughout mission life
- AFRL integration
  - Interface to MSDS electrical system for inhibit removal







## EPS Requirements



- Launch Safety Requirements
  - Two fault tolerant inhibits on all power paths
  - Additional set of two fault tolerant inhibits on STRUCT/MECH subsystem (contact hazard)
  - Fourth inhibit used on each path to bypass inhibit monitoring requirement

## STRUCT/MECH Requirements

- Mission Success
  - Provide structural stability and protection for all nanosat systems
  - Provide position control to enable formation flying – drag panels
  - Provide deployment of 3-meter VLF antenna
  - Provide ability to stack nanosats for launch
  - Provide ability to separate nanosats on-orbit

**STRUCT/MECH Requirements**

- AFRL integration requirements
  - Do not exceed envelope restrictions
  - Provide capability to mount to SSS
- Launch Safety Requirements
  - Structure and all mechanisms must adhere to NASA safety requirements

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**ADCS Requirements**

- Mission Success
  - Determination
    - Measure spin rate within 1deg/sec (GPS and CMT)
    - Measure attitude within 5 deg (VLF)
  - Control
    - Spin rate to within 1 deg/sec in pitch and yaw (GPS)
    - Orient VLF antennas perpendicular to nadir within +/- 10 deg (VLF)

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**ADCS Requirements**

- Launch Safety Requirement
  - Torquer coil magnetic field must be < -170 dBpT (~ 5 gauss ) (we operate with ~ 1 gauss)

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**COMM Requirements**

- Mission Success
  - Provide groundlink and inter-satellite communication
  - Provide low-power communication mode for crosslink
  - Provide sufficient bandwidth to downlink experimental data
- Launch Safety Requirement
  - RF emissions must not exceed levels specified in orbiter payload ICD

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**CDH Requirements**

- Mission Success
  - Provide commanding and data handling capabilities for all nanosat systems throughout mission life
- No integration or safety requirements

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**Experiment Requirements**

- No integration or safety requirements for:
  - VLF
  - MERIT
  - Formation Flying
  - Autonomy

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ROSEMI SSDDL

## Colloid Micro-Thruster (CMT)

- AFRL Integration Requirements
  - Accessible remove-before-flight covers
- Launch Safety Requirements
  - Propellant
    - Non-toxic
    - Non-corrosive
  - Protect ground crew from high-voltage (remove-before-flight covers)
  - Adhere to all NASA structural requirements for sealed containers

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## Command & Data Handling

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## Requirements

- Common system for Emerald and Orion
- Functional Requirements
  - Decode ground and inter-satellite communication
  - Forward commands to distributed subsystems
  - Coordinate/Control Experiments
  - Store/Buffer instrument data
  - Download data to the ground station
  - Control power switching for subsystems and experiments
  - Batch Commands and Scheduling for Operations
  - Gather health and telemetry data

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ROSEMI SSDDL

## Components: Emerald

- CPU (Spacequest)
  - Main command & data
  - Collect Health and Telemetry
  - Scheduling
- Data Bus (Dallas and I2C)
  - Modular connection to subsystems & experiments
- PIC Boards
  - Standard interface for subsystems to data bus
- Bus Monitor
  - Backup command & data
  - Operations Experiments

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ROSEMI SSDDL

## Components: Orion

Science computer

- Provides fast platform for floating-point calculations

SpaceQuest CPU

- V53-based (10 MHz)
- 6 Serial Channels
- 1MB EDAC RAM
- BeKtek OS (COTS)

PIC16F877T Subsystem Microcontrollers

- I2C Interface
- Serial
- 8 A/D Converters
- On-board RAM/ROM

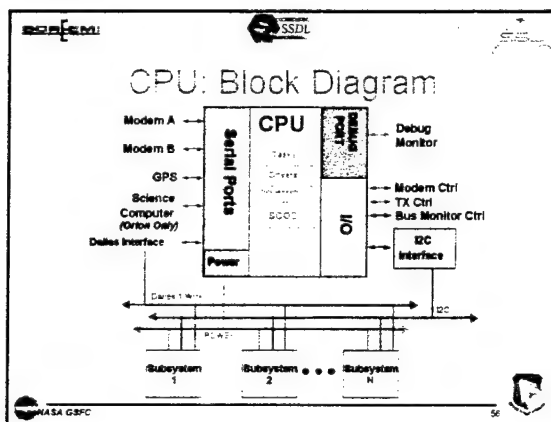
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## CPU: Overview

- Processes Commands
  - Ground
  - Other Satellites
- Routes Information
  - Telemetry
- Scheduling and Experiment Coordination

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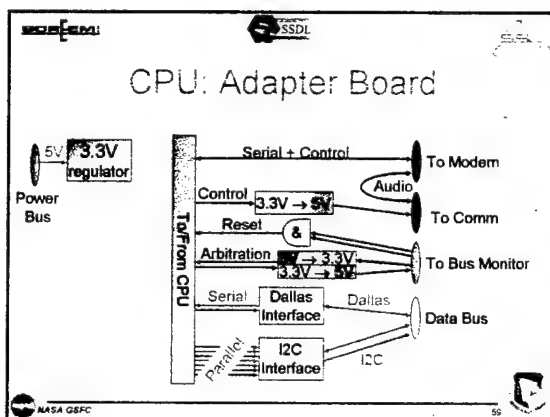


### CPU: Motherboard

- SpaceQuest Rev C
  - NEC V53 processor
  - 10MHz Processor (1MIP)
  - 1MB EDAC RAM
  - 6 Built-In serial channels
  - 40 Digital I/O channels
  - Built-In H/W for interface to S/W TNC

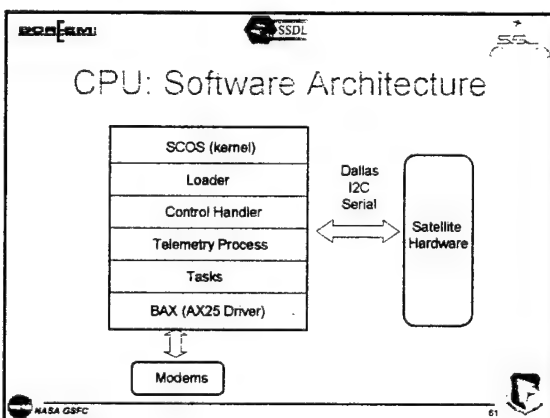
### CPU: Adapter Board

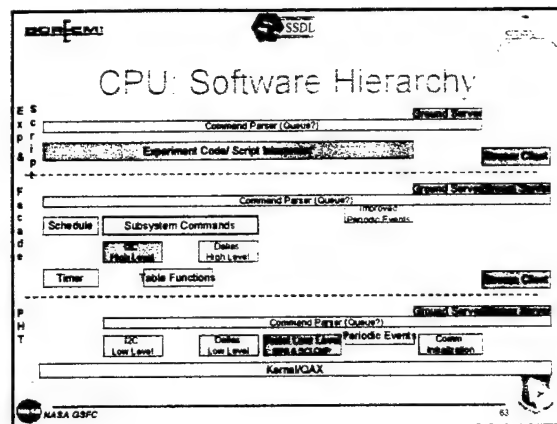
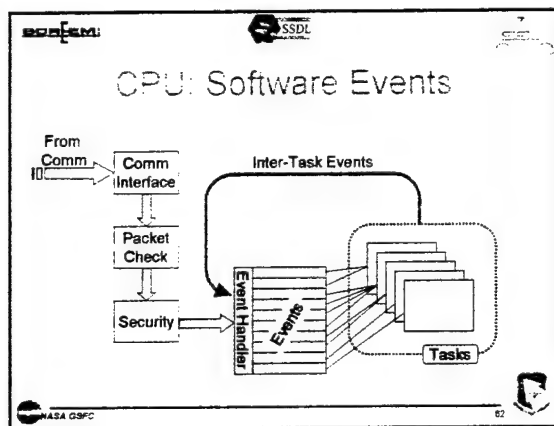
- Purpose
  - Regulate 5V to 3.3V
  - Convert signals 5V ↔ 3.3V
  - House I2C Interface
  - Simplify Wiring Harness



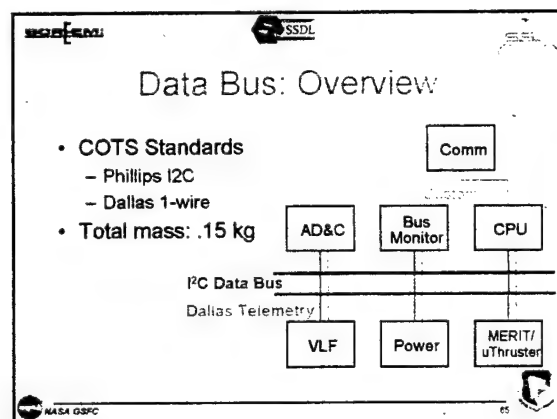
### CPU: Operating System

- Space Craft Operating System (SCOS)
  - From BekTek
  - RAM-based file system
  - Multi-tasking and multi-user
  - Includes S/W for TNC using AX.25
  - Includes H/W and S/W Debugging Utilities
  - Software custom modified to in-house specifications



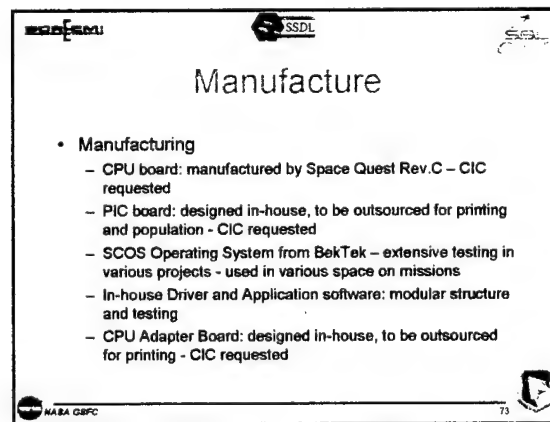
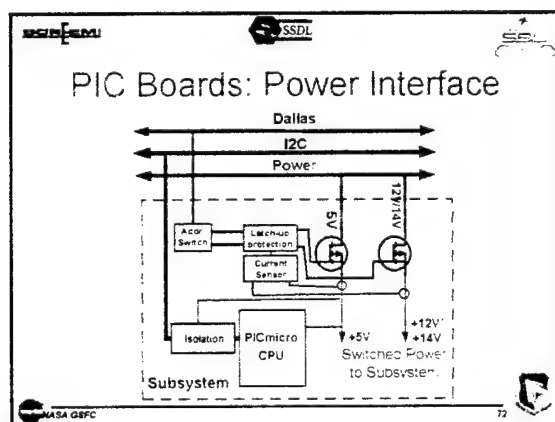
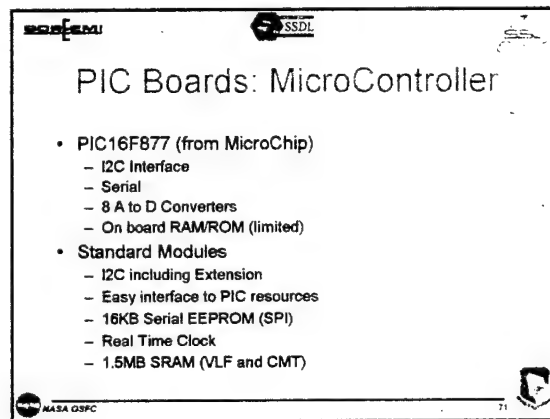
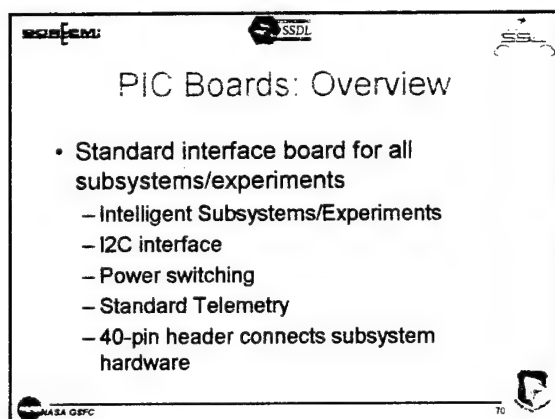
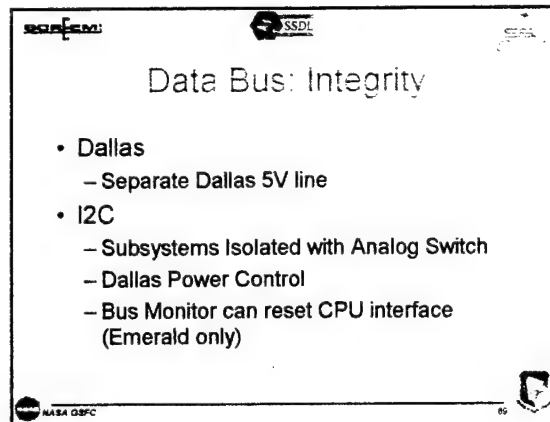
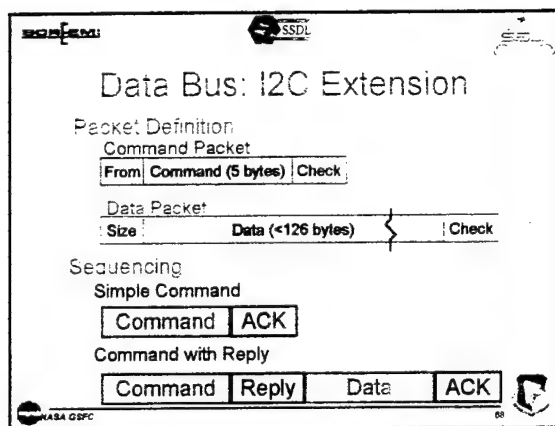


- CPU: Serial Interface**
- Dedicated Link to High Bandwidth Subsystems:
    - GPS
    - Science Computer (Orion Only)
  - Signaling
    - TTL Level (+5V/0V)
    - RS232 Format
  - Up to 57.6 kbps
- NASA GSFC



- Data Bus: Dallas**
- COTS standard by Dallas Semiconductor
    - Asynchronous Serial Protocol
    - Can be powered through Data line
    - <http://www.dalsemi.com/techbriefs/tb1.html>
  - Devices
    - DS18B20: Temperature Sensor
      - $\pm 0.5^\circ\text{C}$  Accuracy ( $-10^\circ\text{C}$  to  $85^\circ\text{C}$ )
      - $-55^\circ\text{C}$  to  $+125^\circ\text{C}$  Max Range
    - DS2450: 4 channel A to D
      - 8-bit resolution
      - Measure Voltages, Currents (with MAX471)
      - Can use at Open Drain Digital I/O
- NASA GSFC

- Data Bus: I2C**
- COTS standard by Phillips Semiconductor
    - Synchronous Serial
    - 2 wires: Clock and Bi-directional Data
    - 100kbps signal rate (max)
    - Multi-master arbitration specified
    - <http://www-us.semiconductors.com/i2c/>
  - Used for Command and Data
    - Subsystems and Experiments
- NASA GSFC



## Testing: Overview

- Modular Design
  - Stand alone basic testing
  - Incremental Integration
- Bottom up testing
- Debug Interfaces
  - SpaceQuest CPU
  - PIC Boards

## Testing: Equipment

- Artic Card (RIC) in PC
  - 80186 (V53 Compatible)
  - High level software testing
  - Modem/Serial interfacing
- PC to Data Bus interface
  - Dallas
  - I2C

## Testing: PC – Data Bus interface

## Testing: Interfaces

- ✓ Dallas Send/Receive
- ✓ I2C Send/Receive (extended)
- ✓ Serial Send/Receive
- ✓ Ax.25 Send/Receive (comm)
- Modem Control (digital I/O)
- Bus Monitor Arbitration (Emerald Only)

## Testing: Full System

- Full Data Path
 

Ground  $\xrightarrow{\text{Serial}}$  Modem  $\xrightarrow{\text{RF}}$  Modem  $\xrightarrow{\text{Serial}}$  CPU  $\xrightarrow{\text{RF}}$  GPS / SciComp

CPU  $\xrightarrow{\text{RF}}$  PIC

CPU  $\xrightarrow{\text{RF}}$  Sensors
- Simulation of Multiple Satellites
 

CPU (Orion)  $\xrightarrow{\text{RF}}$  CPU (Emerald)  $\xrightarrow{\text{RF}}$  CPU (Emerald)

## Safety and Reliability

- Safety Compliance
  - C&DH subsystem powered off until safe distance from the Space Shuttle
  - All components conformal coated to minimize outgassing
- Reliability
  - Memory has 8 bit correctable EDAC
  - Critical functions require both command and confirmation
  - I2C commands require a valid checksum
  - Connectors are staked

# Communications

# Requirements

- Common system for Emerald and Orion
- Functional Requirements
  - Satellite ↔ ground station
  - Satellite ↔ satellite
  - 9600 baud
  - Independent Download for Emerald vs. Orion
  - Receive only Frequency: No jamming

# Components

- Full duplex up/down links, half-duplex cross-link
- 2W DPL power
- 350 mW XPL power
- Omni-directional antenna pattern, circular polarization

SpaceQuest GMSK modem

- in-house assembly and test
- AX.25 protocol, 9600 baud max data rate

Hamtronics FM TX/RX kits

# Specifications

- Full Duplex, Mode J (amateur)
  - 2m Uplink
  - 70cm Downlink
- Half Duplex Crosslink (70cm)
- Omni-directional antennas with circular polarization.

# Frequency Scheme

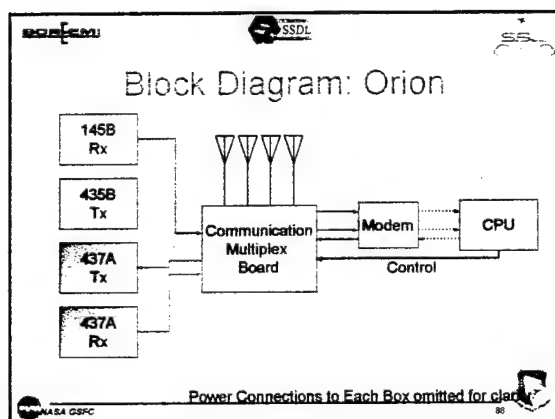
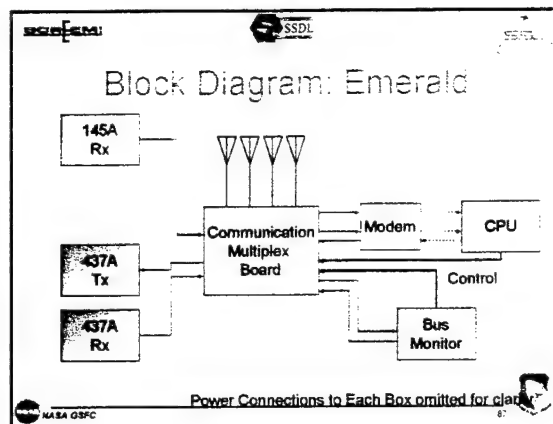
# Modem

- Manufactured by SpaceQuest
- GMSK encoding
- Dual Channel
  1. 9600 baud fixed
  2. Software adjustable (9600 baud max)

**Comm Multiplex Board**

- Push-to-talk (PTT)
  - High Power (2W)
  - Low Power (350mW)
- Polarization Control
- Antenna Matching
- Supports fully Redundant system:
  - 2 Control/Signal Sources
  - 2 Transmitter/Receiver Pairs

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**Manufacturing**

- Radios: Hamtronics FM TX / RX kits modified for the space environment; In-house assembly and test\*  
 \*modifications: crystals, tantalum capacitors, removal of audio amp in Rx
- Satellite modem: SpaceQuest GMSK modem – CIC requested
- Comm Multiplex Board: In-house design, assembly and test. Board manufacture: Advanced Circuits

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**Testing**

- Component Testing
  - individual radio functionality/tuning
  - Modem configuration
  - Modem data transfer
  - Multiplex Board switching
- Interface Testing
  - CPU (and Bus Monitor)
  - Ground Station
- Incremental Testing (add links to middle of chain)
- Full System Test (see C&DH section)

NASA GSFC

**Safety**

- Comm subsystem will be powered off until safe distance from the Space Shuttle
- Comm power supply inhibited by power subsystem (2 fault tolerant)
- All components will be conformal coated to minimize outgassing

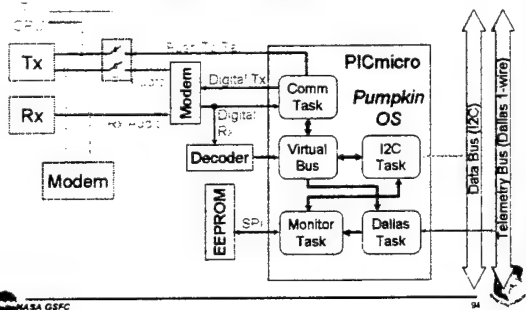
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## Bus Monitor

## Design Overview

- Monitors State and Activity of Data Bus
- Provides Direct Access to Data Bus
  - CPU Backup
  - Operations Experiments
- Can Achieve minimum functionality of all components on the Bus
- Separate Modem

## Block Diagram



## CPU Arbitration

- Comm interface board has hardware switch
  - CPU must send pulse to keep control
  - Tx, PTT, Power Level Control
- Direct CPU connection
  - Request Comm Control
  - Reset CPU's I2C interface
  - Reset CPU (requires 2 signals)

## Performance

- I2C Master – 80 kbps (max)
- Dallas Master – ~1 kbps
- Modem Interface
  - 1200 baud
  - AFSK (Bell 202)
  - Half Duplex

## Manufacture

- Manufacture
  - Manufactured by Advanced Circuits
  - Assembled by contractor
- Fabrication and assembly will adhere to published assembly instructions for all circuitry and hardware

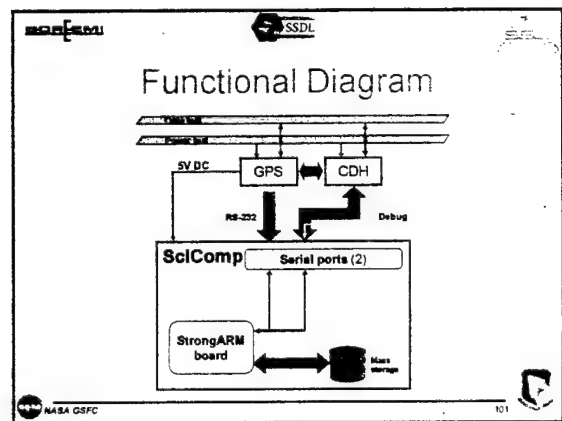
Test

- Functional testing of all circuitry
- Communication Control Switching
- Communication Control Arbitration
- CPU's modem signal rejection
- RF ↔ Modem ↔ Bus Monitor ↔ PIC

Safety

- C&DH subsystem powered off until safe distance from the Space Shuttle
- All components conformal coated to minimize outgassing
- CPU can prevent Bus Monitor control of Comm System

Science Computer



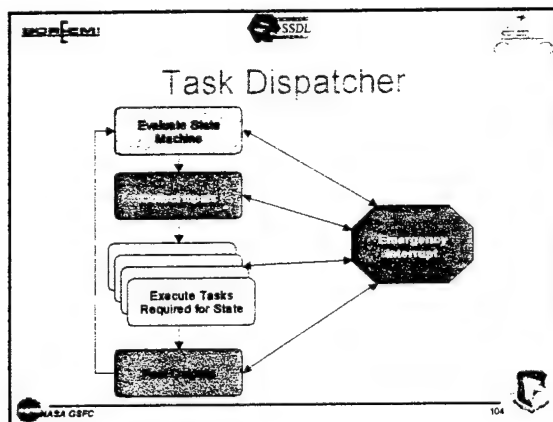
Hardware

VS

<ul style="list-style-type: none"> <li>• StrongARM 1100 CPU</li> <li>• Power: 2W</li> <li>• Memory: 4 MB flash, 32 MB RAM</li> <li>• Comm: 2xRS-232 (no handshake), 1xRS-422</li> <li>• Limited Supply</li> <li>• EM Development Purposes</li> </ul>	<ul style="list-style-type: none"> <li>• StrongARM 1110 206MHz CPU</li> <li>• Power: 2W</li> <li>• Memory: 16 MB flash, 8-64 MB RAM</li> <li>• Comm: 3xRS-232, GPIB</li> <li>• COTS (two week delivery time)</li> <li>• Proposed Flight Units</li> </ul>
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Software Development

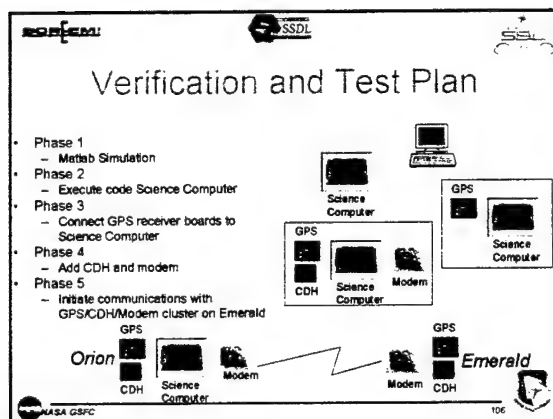
- ARM Linux
  - Low Overhead
  - Low Cost
  - Versatile
- Realtime Issues
  - Realtime OS not needed
  - Low Bandwidth (< 10 Hz)
  - Write custom task dispatcher
- PC Code Generation
  - Translate Matlab M Functions into C
- Linux Software Compilation
  - GNU C Cross Compiler
  - Download Ramdisk into StrongArm



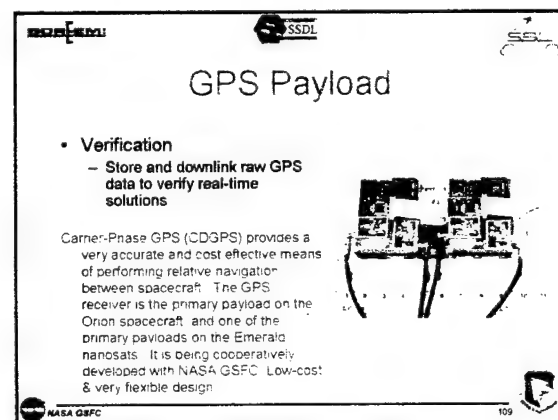
### State Flow / Task Breakdown

Task	Shuttle Launch	Launch Phase	Wait for Separation	Stabilize Formation	Standby	Change Formation	Deorbit
GPS		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Att. Ctrl				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
Fuel Reg.				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Estimation	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Modeling	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Form. Coord				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Keep Alive	<input checked="" type="checkbox"/>						

NASA GSFC 105



- ### GPS Payload
- GPS receiver
    - Power 8 W peak & 2 W "rest" mode
    - ~1kg & 12cm x 20cm x 25cm
    - 6 antennas (option for 8)
    - ARM60B and Strong ARM processors for navigation processing
    - Extensively tested on ground
  - Based on Mitel Chipset
    - GP2015 RF front end
    - GP2021 12 channel correlator
    - Radiation tolerant
    - External clock linking micro-controller RF front ends
- NASA GSFC 108



The diagram illustrates the hardware components of a GPS receiver. On the left, three identical vertical blocks represent the receiver modules, each containing a microcontroller, memory, and various interface chips. These are connected to a central vertical block representing the antenna and its associated electronics. To the right, two photographs show the physical hardware: the top one is a close-up of the receiver module, and the bottom one is a photograph of the antenna assembly. Labels with leader lines identify the 'GPS Receiver Module', 'GPS Receiver Antenna', 'Power Management and Control', and 'External GPS'.

A presentation slide titled "GPS Receiver Software". The slide features a header with the "SSDL" logo and a small satellite image. The title is in a large, bold, sans-serif font. Below the title, the word "Features:" is followed by a bulleted list of five items. The first item, "Clock slews to synchronize with GPS time", has a sub-bullet "Receivers on different vehicles still coordinated". The second item is "Improved Tracking Loops", with a sub-bullet "FLL for acquisition, PLL for tracking". The third item is "Cycle Slip Detection". The fourth item is "Orbit propagator", with a sub-bullet "Necessary for LEO initialization". The fifth item is "Relative orbit propagator and navigation algorithm". The slide has a black border and a small NASA GSFC logo in the bottom left corner.

SSDL

# GPS Receiver Software

Features:

- Clock slews to synchronize with GPS time
  - Receivers on different vehicles still coordinated
- Improved Tracking Loops
  - FLL for acquisition, PLL for tracking
- Cycle Slip Detection
- Orbit propagator
  - Necessary for LEO initialization
- Relative orbit propagator and navigation algorithm

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High Fidelity Sim:  
Position Error

Carrier Phase Relative Position Error

EKF solution of GPS measurements using truth file generated using GSFC Trajectory Determination System Simulation

$\sigma = 1-3 \text{ cm}$

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High Fidelity Sim:  
Velocity Error

Range Velocity Error

Azimuth Error

Cross-track Error

EKF solution of GPS measurements using truth file generated using GSFC Trajectory Determination System Simulation

$\sigma = 1-2 \text{ mm/sec}$

**Predicted GPS Results**

	$\mu$	$\sigma$
<b>Absolute Pos (m)</b>	<b>33.9</b>	<b>18.7</b>
<b>Relative Radial Position (cm)</b>	<b>1.3</b>	<b>3.22</b>
<b>Relative In-track Position (cm)</b>	<b>1.4</b>	<b>2.27</b>
<b>Relative Cross-track Position (cm)</b>	<b>1.8</b>	<b>1.45</b>
<b>Relative Radial Velocity (mm/s)</b>	<b>0.17</b>	<b>1.8</b>
<b>Relative In-track Velocity (mm/s)</b>	<b>0.26</b>	<b>1.1</b>
<b>Relative Cross-track Velocity (mm/s)</b>	<b>0.14</b>	<b>1.0</b>

- Matlab predicted estimation errors for realistic on-orbit scenario - includes bias acquisition.
- Currently developing hardware in the loop tests to verify these results/assumptions

**Ground Test Results**

Receiver - Relative Position

Relative Relative Velocity

Demonstration of real-time relative position and velocity estimate error using current modified receiver in ground-based test.

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**SOLEM** **SSDL**

## Manufacture and Test

**Milestones**

- **Hardware development**
  - Prototype of GPS receiver and interface board complete
  - Complete integration
  - Minor mounting and shielding work
- **Software development**
  - Implement navigation and attitude algorithms previously developed in MATLAB in C
  - Run on ARM60 or Science Computer
- **Test terrestrial performance**
- **Test using GSFC GNC GPS signal simulator**
  - Use of simulator facility during development helped improve software design and will streamline testing

NASA GSFC 116

**SOLEM** **SSDL**

## Development

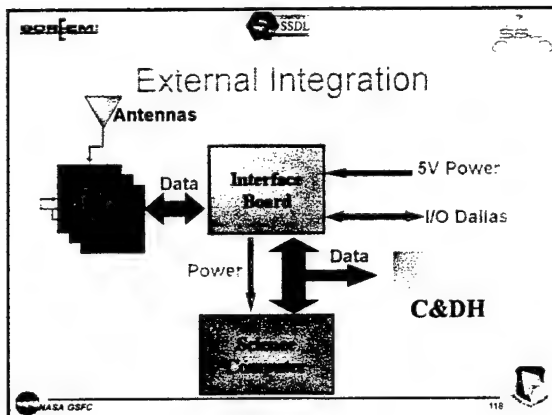
**Navigation Algorithms** MATLAB C code Embedded

**Receiver Hardware** Prototype Receiver Boards Interface Board Flight Models

**Receiver Operations** Orbit Prop. Fast Acq. Tracking Loops

**External Integration**

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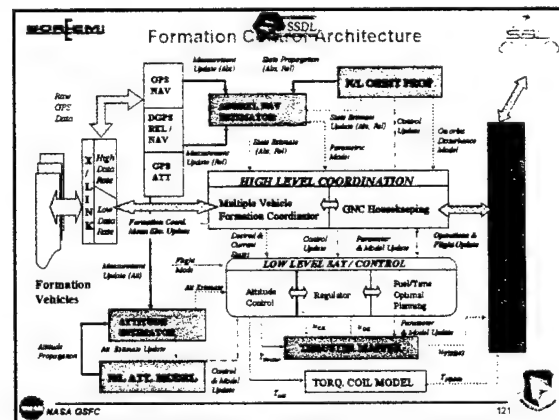
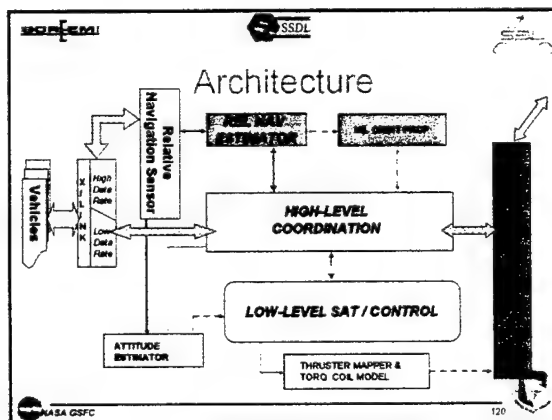


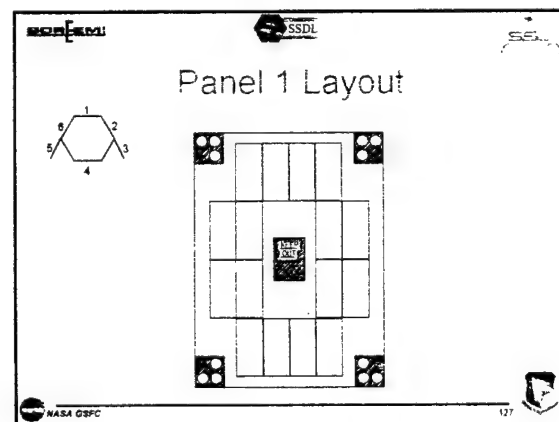
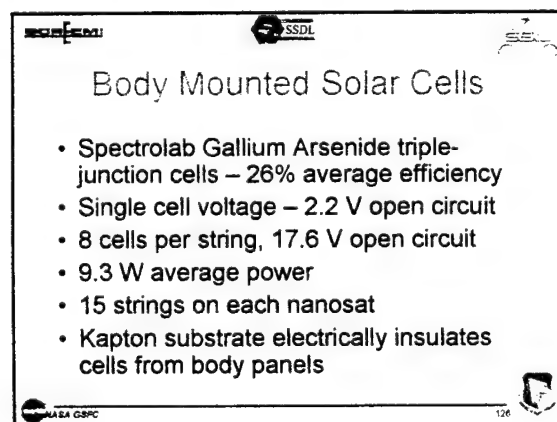
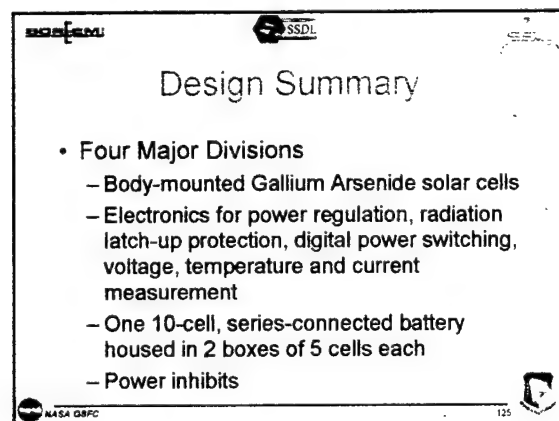
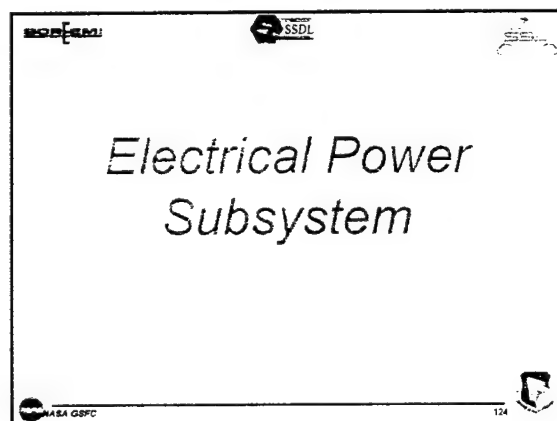
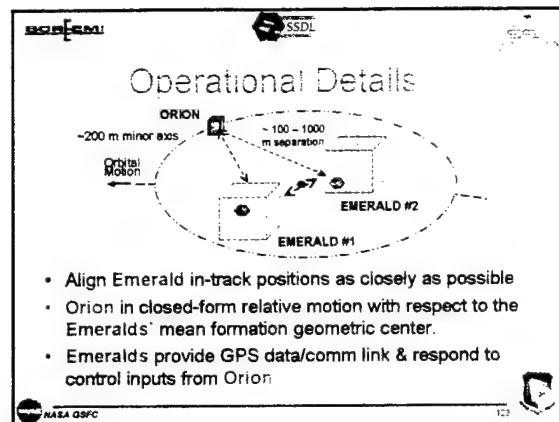
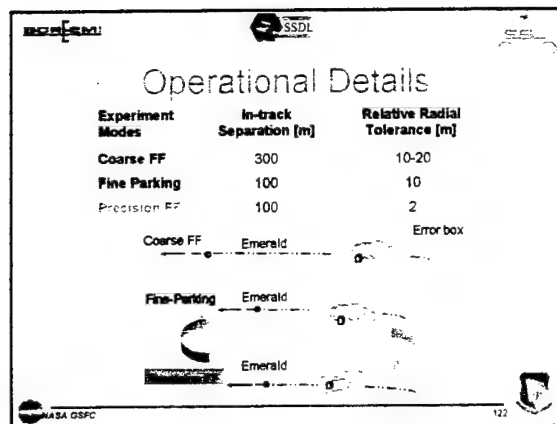
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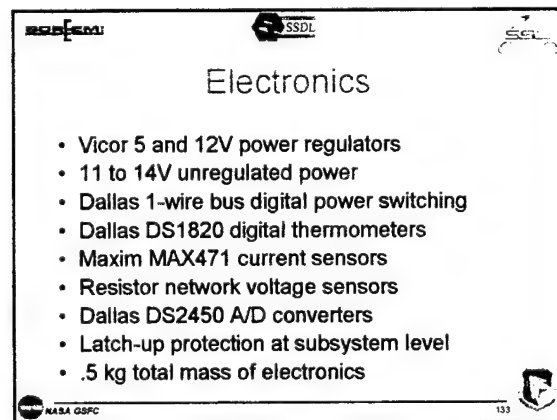
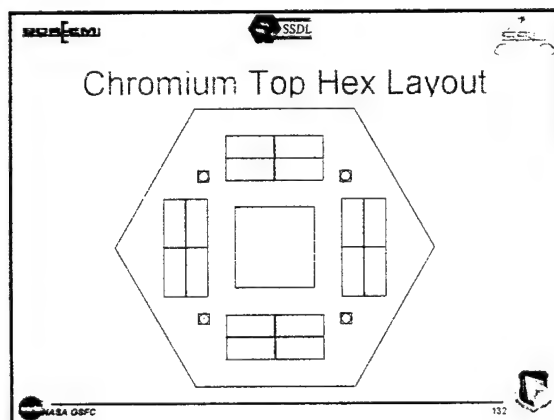
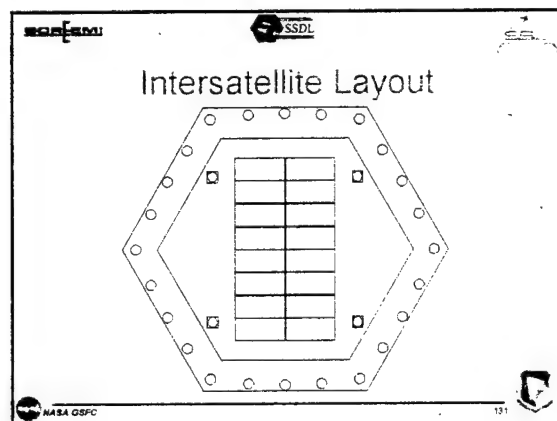
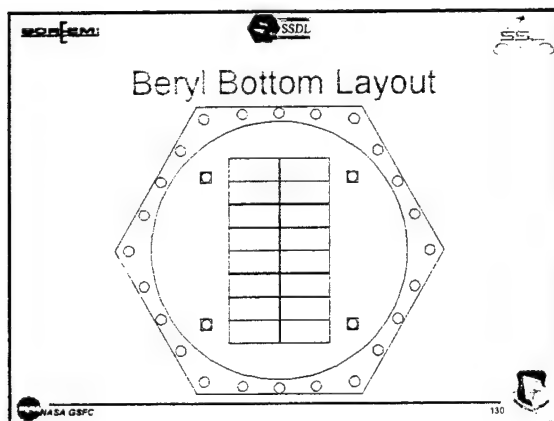
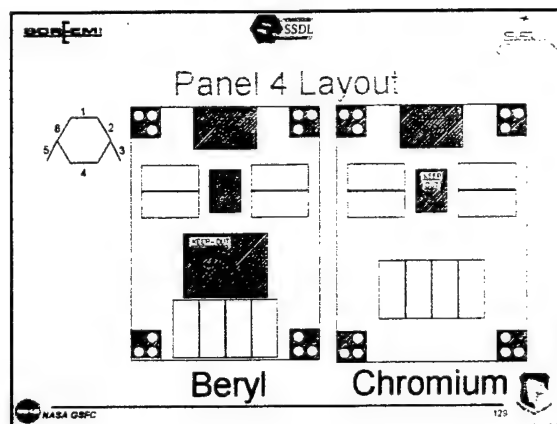
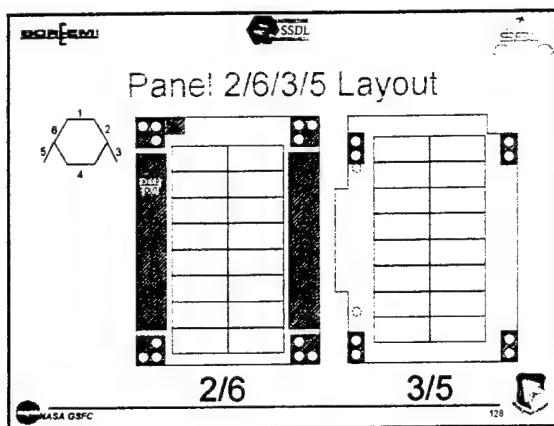
## Control Features

- GPS receiver collects carrier, code, & Doppler measurements
  - Cross-links data to other formation vehicles
  - Inputs into estimator: absolute/relative navigation, attitude
- Absolute and relative estimators filter data with orbit propagators
  - Navigation estimate sent to high level formation coordinator
  - Attitude to low level vehicle controller
- High level coordinator commands all formation vehicles based on current operating mode

NASA GSFC 119







# Power Distribution

- Dallas 1-Wire serial bus for Power Switching
- 3 distribution buses
  - 2 for general use
  - 1 for noisy/high power draw
- Standardized DB9 pin-out

Diagram illustrating the power distribution buses and their connection to ground:




- 5 volts
- 12 volts
- unregulated
- Clean gnd
- Dirty gnd

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- 
- Diagram of a 12-volt battery with 5 volts and 12 volts terminals, and unregulated and Clean gnd terminals.

## Battery

- One 10-cell, series-connected battery housed in 2 boxes of 5 cells each
- Sanyo CADNICA 5 AH KR-5000DEL cells
- Family of cells has flown on manned missions
- Each box is a sealed 6061 aluminum container
- 1.1 kg per box (including cells)

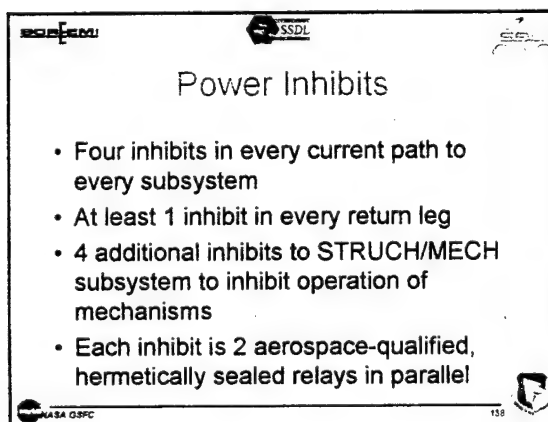
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## Battery Box

  - 2 valves on "high" side of box
  - Sub-micron filters to trap electrolyte
  - Interior coated with non-conductive electrolyte resistant paint
  - Positive terminals packed with electrolyte-absorbent material
  - Purged with dry N<sub>2</sub> to 20psia
  - Teflon cell spacers
  - Internal digital Temp./Press. sensors
  - Viton O-ring to seal lid

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- # Battery Box
- 
- An exploded view diagram of a battery box assembly. The components shown are:
- O-ring**: A circular seal located at the bottom left of the main assembly.
  - lid**: A rectangular cover plate positioned above the main assembly.
  - batteries**: A group of four rectangular battery cells arranged in a 2x2 grid within the main assembly.
  - terminal**: A small component located at the bottom right of the main assembly, near the batteries.
- The main assembly is a rectangular box with a lid and a base. The batteries are shown in an exploded view, indicating they are inserted into the box. The terminal is also shown in an exploded view, indicating it is attached to the bottom of the box.



- 
- The diagram illustrates the power distribution and inhibition logic for a system. Key components and their connections include:
- Solar Panel x 8:** Provides input to the system via a switch labeled '1'.
  - Battery:** Consists of two NiCd batteries (Battery 1 and Battery 2) connected in series. It is controlled by a 'Master Battery Disconnect' switch (labeled '1') and a 'Current Sensor'.
  - Power Regulator:** Features a 'CVF Regulator' and an 'AV Regulator'. It receives input from the battery and provides output to the system.
  - System Components:** Includes a 'VLF antenna', 'Ding Panels', 'Lightmeter operation circuit', and 'All other Systems'.
  - Wiring and Signals:** Various wires are labeled, including 'WIRE 1' through 'WIRE 10', 'WIRE 11' (labeled '11' signal'), and 'WIRE 12' (labeled '12' signal').



**Power-Up Sequence**

- Separation from Orbiter
  - All systems not powered
  - All inhibits not monitored
- T1 Signal from MSDS Platform
  - All systems powered except STRUCH/MECH
- T2 Signal from MSDS Platform
  - STRUCH/MECH system powered

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**Design Analysis**

- Performance Analysis
  - Expected power output
- Structural Considerations
  - Battery Box
- Thermal Considerations
  - Batteries
  - Electronics

NASA GSFC 141

**System Performance**

Cell		Power Output	
Cell voltage	1.2 volts	Cell size	3.36 sq. in.
Cell capacity	5 AH	Cell current	264 mA
# of cells/box	5 cell	Cell voltage	2.2 volts
# of packs	2 packs	S. Area to light	53.6 sq. in.
		Time illuminated/orbit	78.3 min.
Power output	6 watts/box	Cell Power Output	580.9 mW
Total capacity	5 AH	Cell Power Output Area	172.657 mW/sq.in.
Power energy storage	30 Wh/box	Area Power Output	9299.714 mW
Total energy storage	60 Wh	Area energy output	12.105 Wh

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**Battery Box Structural Analysis**

- Must support mass of batteries
  - Battery mass, .75 kg per box
  - 20G dynamic load, 15 kg
  - 4 feet, .125 sq. in. area per foot
  - 66 psi total shear load on box feet
  - FS of 227 on foot strength
  - May reduce size of feet
- Must hold 20 psi internal pressure
  - .25 in. thick walls
  - FS of 10000
  - May reduce thickness of box walls

NASA GSFC 143

**Thermal Analysis**




- Battery the only critical component
- Battery thermal requirements
  - Charge
    - 0-45 deg. C.
  - Discharge
    - -20-60 deg. C.
  - Storage
    - -30-50 deg. C.
- Thermal finite element model shows compliance with these limits for on-orbit operation.

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**Battery Box Manufacture**


- Materials
  - 6061 T6 Aluminum box structure
  - Teflon Battery Spacers
  - Fiberglass absorbant material
  - Vitron O-ring
  - 2 20 psi cracking check valves
  - Hermetic connector
- All parts of the EPS are non fracture critical

NASA GSFC 145








## Battery Box Manufacture

- Construction
  - Boxes milled from aluminum
  - Spacers milled from Teflon
  - O-ring custom made
  - Check valves threaded into box
  - Hermetic connector threaded into box
  - Batteries set in spacers and potted




NASA GSFC 145








## Electronics Manufacture

- Custom boards manufactured by Advanced Circuits and built at Stanford University
- Standard PicMicro board
- Fabrication and assembly will adhere to published assembly instructions for all circuitry and hardware




NASA GSFC 146








## Test

- Battery Box
  - Proof test to 20 psi
  - Leak test (digital pressure sensor)
- System functional test




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## Ground Operations

- Battery box to be sealed and purged at the universities
- Inhibits disabled, reset, and verified through the STPI
  - Procedure will be listed here
- Batteries charged through the STPI
  - Procedure for charging will be here
  - 6 month time limit between charges, based on heritage experience with batteries from OPAL




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## Requirements Fulfillment


- System meets power needs of spacecraft as designed
- Inhibit scheme adequately prevents power accidentally being applied



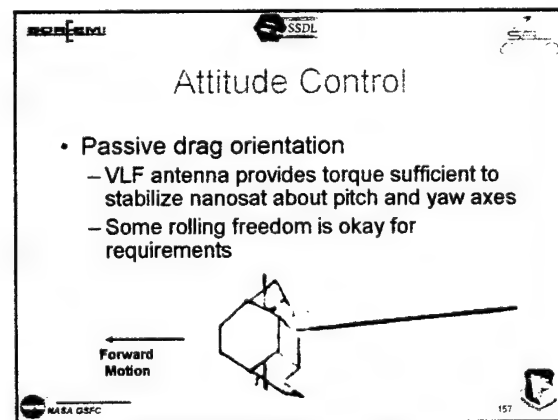
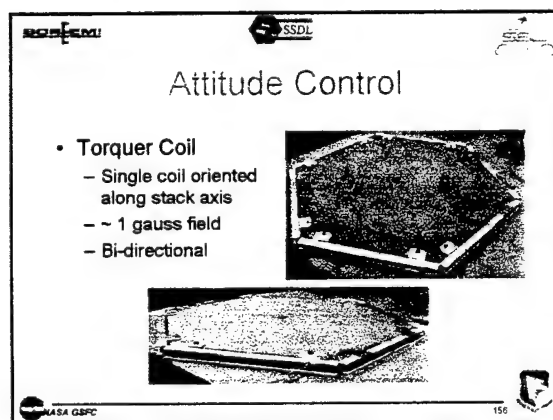
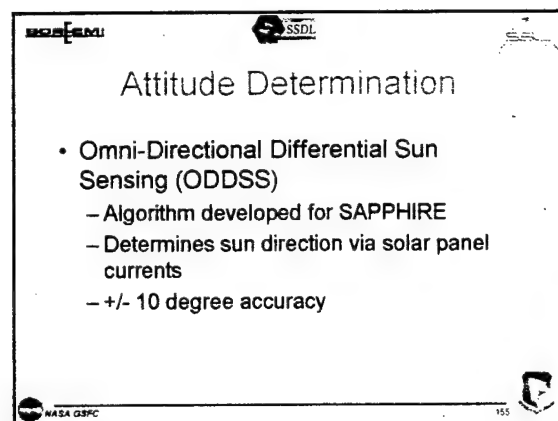
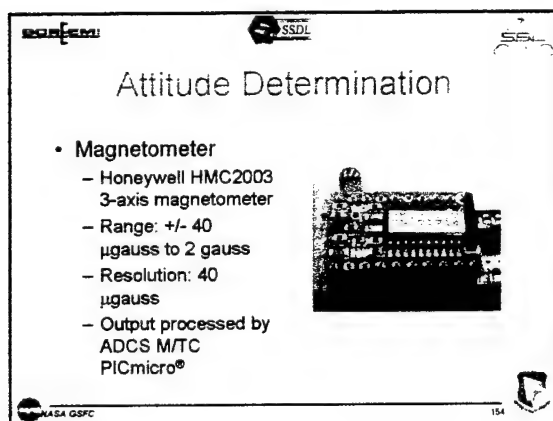
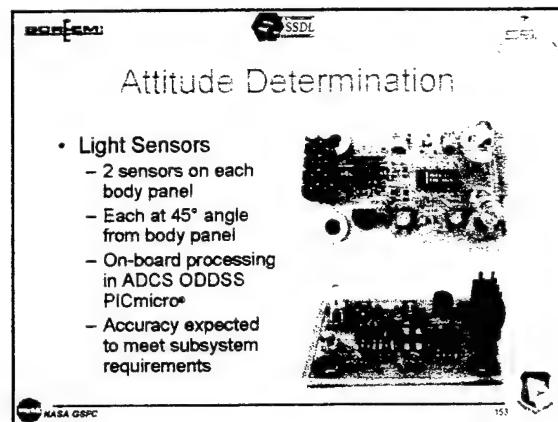
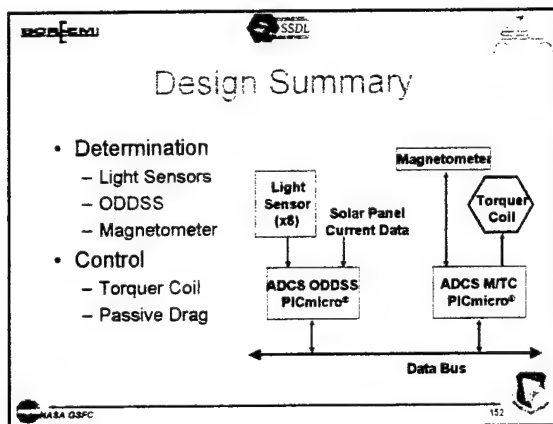
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## Attitude Determination and Control (ADCS)



NASA GSFC 151



Materials

- Light sensor, magnetometer, ODDSS
  - Electronic components
  - Custom-manufactured PCB
- Torquer Coil
  - Aluminum frame
  - Magnet wire
  - Epoxy: Stycast 2850FT w/ Catalyst 9

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Mass & Fracture Control

- Mass
  - Electronics: 0.5 kg
  - Torquer Coil: 0.5 kg
- Fracture Control
  - No portions of the ADCS are fracture-critical

NASA GSFC 159

Design Analyses

- Analyses performed:
  - Separation analysis
  - Drag stabilization analysis
  - Torquer coil stabilization analysis

NASA GSFC 160


Separation Analysis

- Objective: determine optimal stack orientation for separation
- Goal: Separate stack such that resulting orbits are close together
- Examine two separation possibilities
  - In-track separation
  - Out-of-plane separation
  - Radial separation not feasible with available attitude control capability

NASA GSFC 161

Separation Analysis

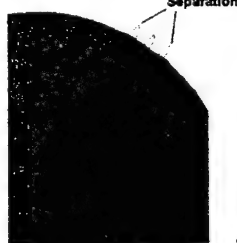
- In-track separation
  - Can compensate for separation velocities using drag panels
  - If drag panels fail, satellites separate by ~250 km/day – only 10 hours of crosslink
  - If drag panels work, compensation takes ~20 days




NASA GSFC 162

Separation Analysis

- Out-of-plane separation
  - Causes inclination change – worst case 0.8 km
  - J2 perturbations add 3 km separation per month
  - Acceptable for mission success
  - Can achieve via torquer coil orientation & separation at northern- or southern-most part of orbit


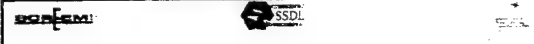


NASA GSFC 163




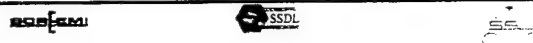
## Manufacture

- Custom boards manufactured by Advanced Circuits and built at Stanford University
- Standard PicMicro board
- Torquer coils constructed at Stanford University
- Fabrication and assembly will adhere to published assembly instructions for all circuitry and hardware

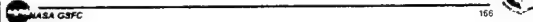

## Test

- Functional testing performed on all circuitry and hardware

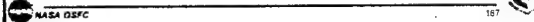

## ADCS Ground Operations

- No ground operations required






## Requirements Fulfillment

- Mission Success
  - The light sensors and magnetometer fulfill determination requirements
  - Passive drag stabilization meets operational requirements
  - Torquer coil stabilization allows optimal separation orientation
- Launch Safety Requirements
  - Torquer coil field well below limit





## *VLF Receiver Experiment*

## Experiment Objectives

- Mission Statement
  - This atmospheric science experiment utilizes a set of VLF receivers (one on each spacecraft) to detect electromagnetic disturbances due to lightning.
- Mission Objectives
  - Characterize the ionosphere
  - Validate benefits of formation flying
  - Perform a comparative study of how satellite size and processing architecture impact a baseline science mission



## Design Summary

- VLF Receiver
  - Bandpass filter with peak amplification at 4KHZ
- PIC16C77 Microchip
  - 8K program memory
  - 20 MHz sampling speed
- External SRAM
  - Allows for an extra 1.0 M RAM
- Total mass .5 kg, including antenna

## Operations

- Receiver Duties
  - Filter low frequency (1-10 kHz) EM disturbances
  - Amplify signal
    - Received wave 100-300 mV, Output wave 500-1000 mV
- PIC Processor duties
  - Sample VLF receiver data / store to PIC memory
  - Read PIC memory / send data across I2C Bus
  - Science data tagging
    - Time, attitude, absolute & relative positions

## Manufacture

- Custom boards manufactured by Advanced Circuits and built at Stanford University
- Standard PicMicro board
- Fabrication and assembly will adhere to published assembly instructions for all circuitry and hardware

## Test

- Functional testing of all circuitry

# MERIT

## Experiment Objectives

- MERIT: Micro Electronic Radiation In-flight Testbed
- Testbed for Measuring Effects of Radiation
- Modularity
  - Host
  - Device Under Test (DUT)
- Easy Expandability
  - Low power consumption
  - Small Size

**Design Summary**

- Modular architecture
  - Primary Host Board
  - SPI bus to testbed
  - SPI bus to DUTs
- Total mass: .65 kg

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**Hierarchy**

NASA GSFC 177

**MERIT Testbed**

- Dosimetry Unit
  - Three 4007s (3 PFETs each)
  - Temp sensor for each 4007
- Single Event Upset Detector
  - Two 512kword SRAM
  - Three 4520s (sync. binary counter)
- 3 10 pin DUT headers
  - Supplies power and SPI signals

NASA GSFC 178

**MERIT Host**

- Communicates with Emerald Host via I2C
- Communicates with MERIT testbed and DUTs via Serial Peripheral Interface (SPI)
- Responsible for coordinating DUT testing and storing experimental data waiting for downlink

NASA GSFC 179

**MERIT Operations**

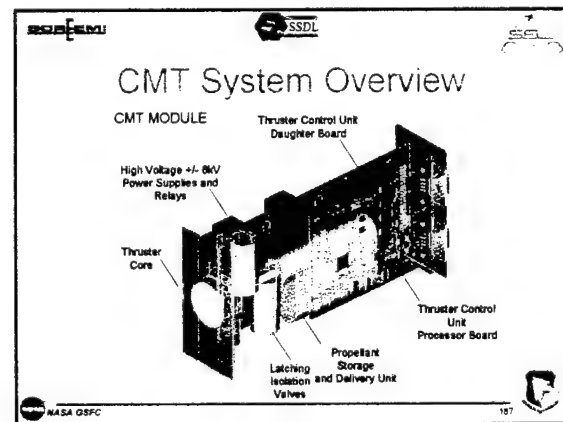
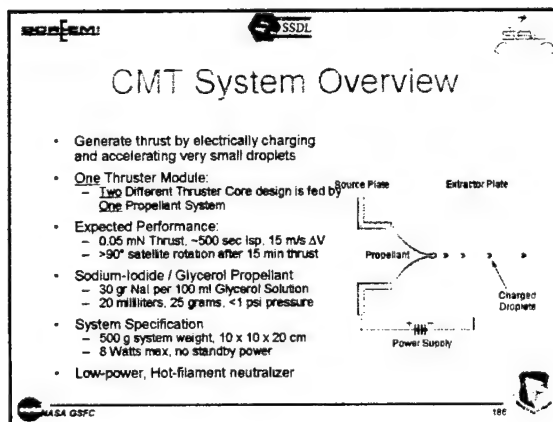
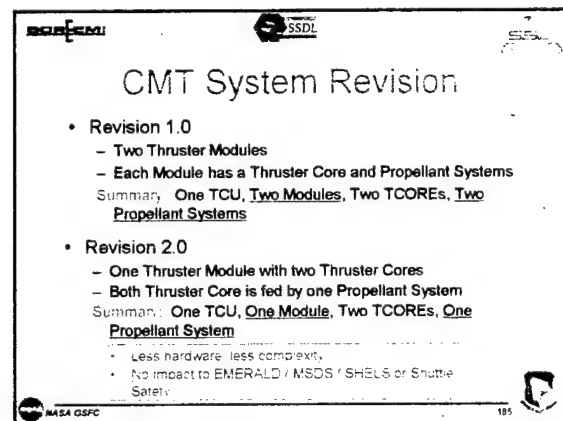
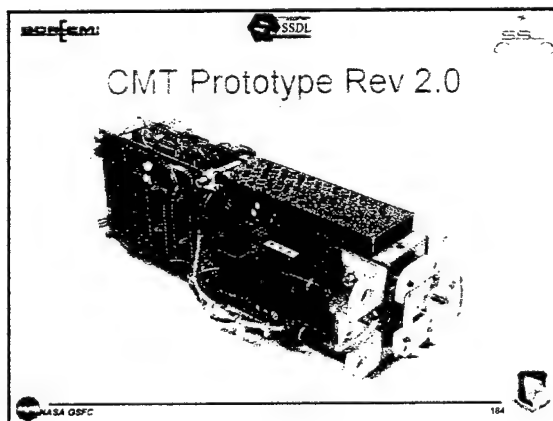
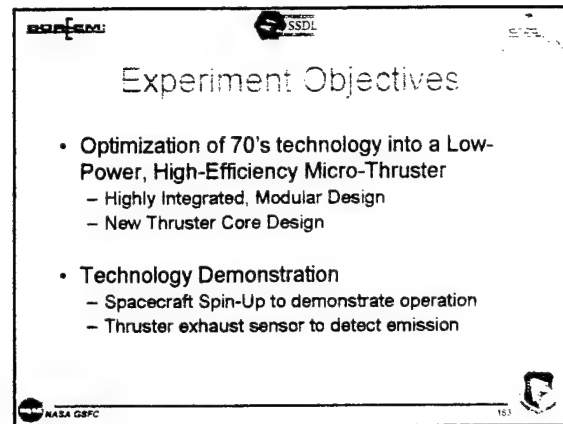
- Dosimeter
  - Test Mode (5% of time)
  - Accumulation Mode
- SEU Detector
  - Write 4 different bit patterns
  - Read Memory contents recording SEUs

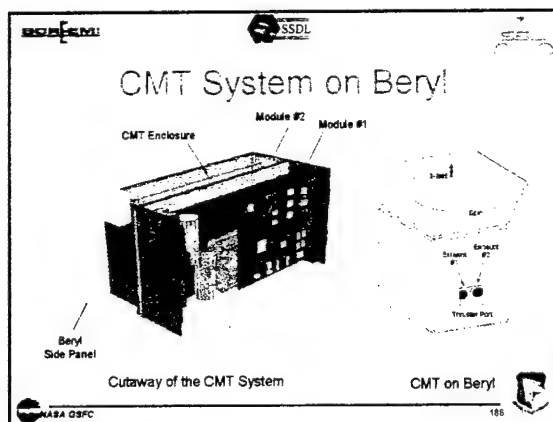
NASA GSFC 180

**Manufacture and Test**

- Manufacture
  - Custom boards manufactured by Advanced Circuits and built at Stanford University
  - Standard PicMicro board
- Fabrication and assembly will adhere to published assembly instructions for all circuitry and hardware
- Test
  - Functional testing of all circuitry

NASA GSFC 181





**CMT Thruster Control Unit**

- Function of TCU:
  - Controls all CMT functions and communicates with the spacecraft main computer
- TCU Components
  - Digital logic:
    - PICmicro® 16F877 Microcontroller
    - Digital to Analog Converter
    - Analog Multiplexer
    - Random Access Memory for Data Storage
    - Picoammeter and Temperature Sensors
  - High-Voltage Power
    - +6kV and -8kV Power Supplies

**CMT Capillary Thruster Core**

- Function of TCORE
  - Generate thrust using charged sub-micron particles
- Thruster Module #1
  - "Tradibonal" Design
- TCORE Components
  - Pipe Emitter
    - 150  $\mu\text{m}$  OD / 50  $\mu\text{m}$  ID
  - Source Plate (SS304)
  - Extractor Plate (SS304)
  - Insulator (Boron-Nitride)
  - Propellant Chamber (Teflon)

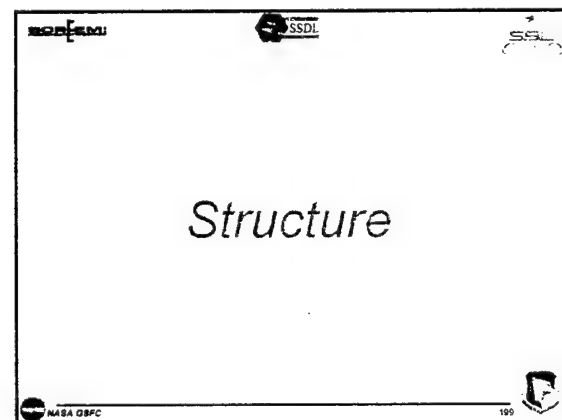
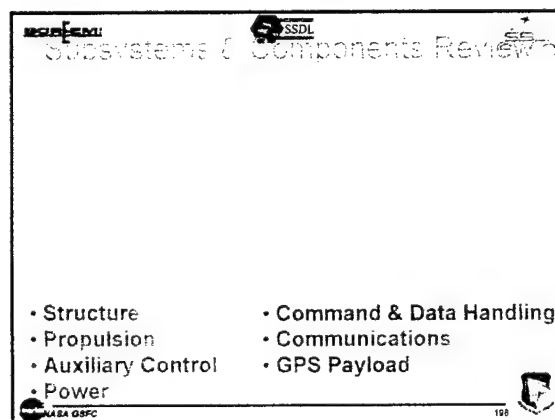
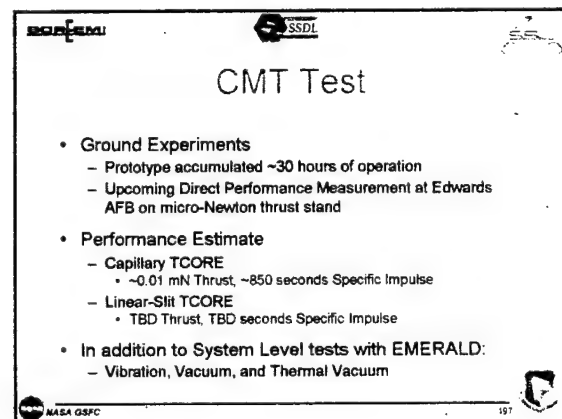
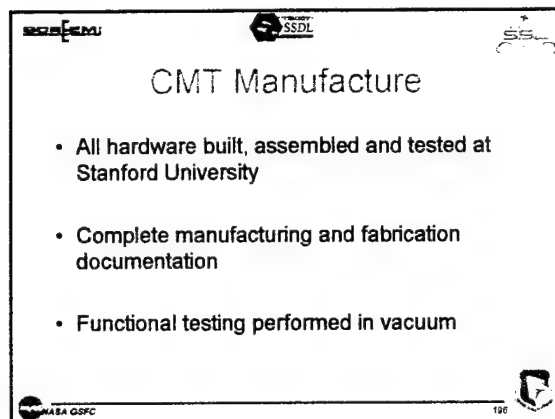
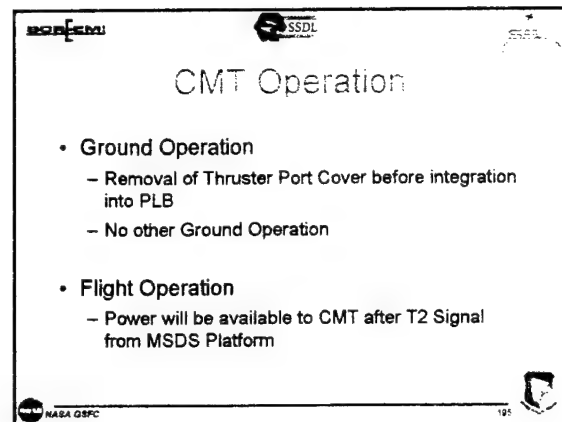
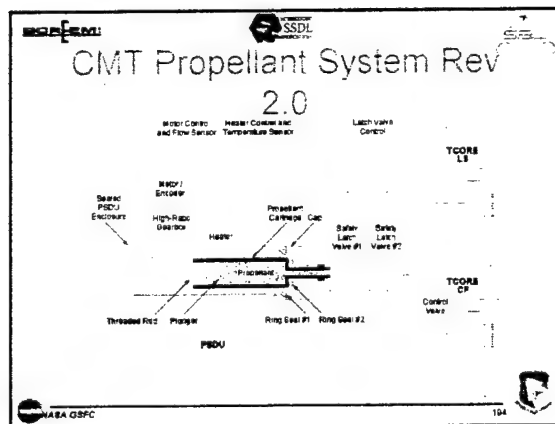
**CMT Linear-Slit Thruster Core**

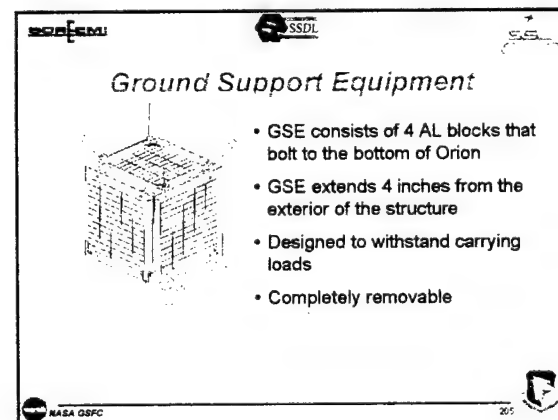
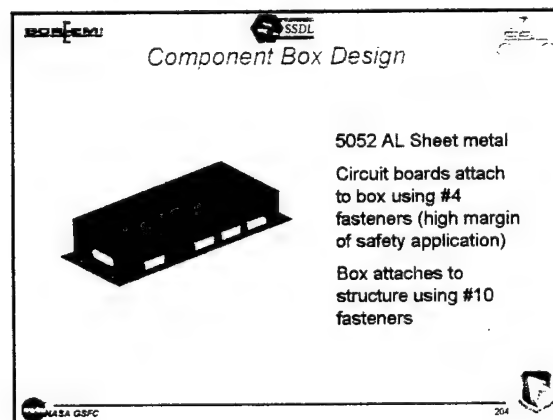
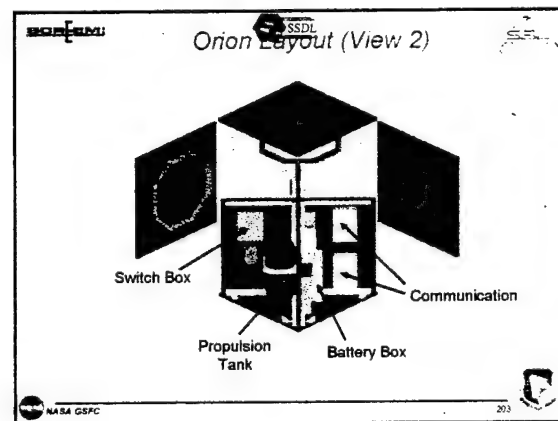
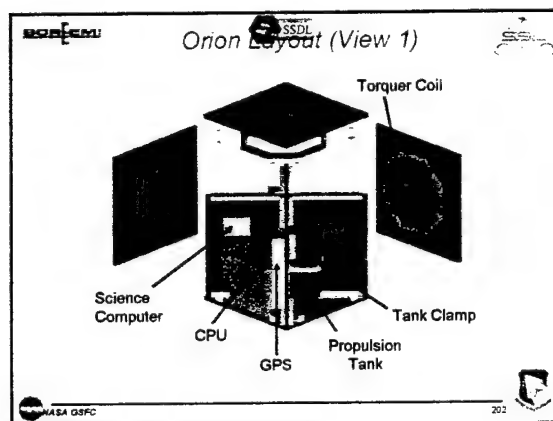
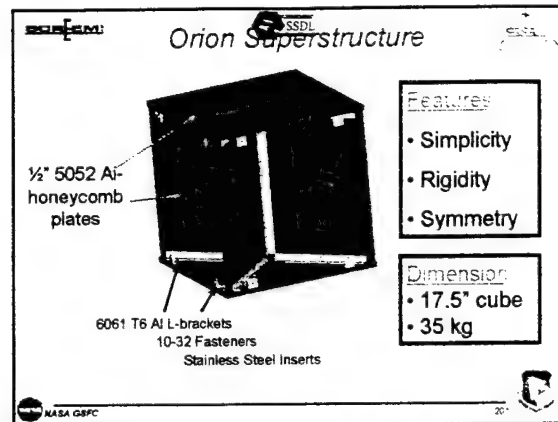
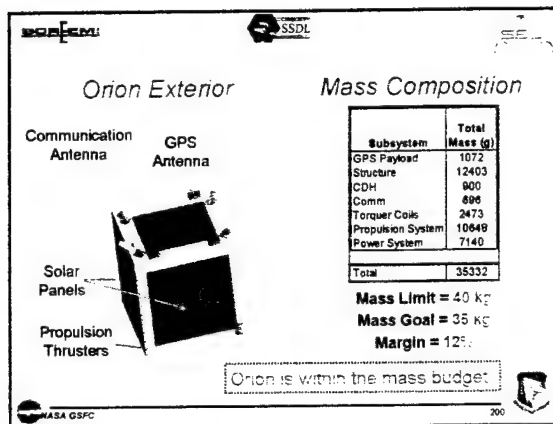
- Function of TCORE
  - Generate thrust using charged sub-micron particles
- Thruster Module #2
  - Manufacturing, Robustness advantage
- TCORE Components
  - Plate Source (Hardened SS)
    - Plate-Rake-Plate sandwich construction
  - Extractor Plate (SS304)
  - Insulator (Teflon / BN)
  - Propellant Chamber (Teflon)

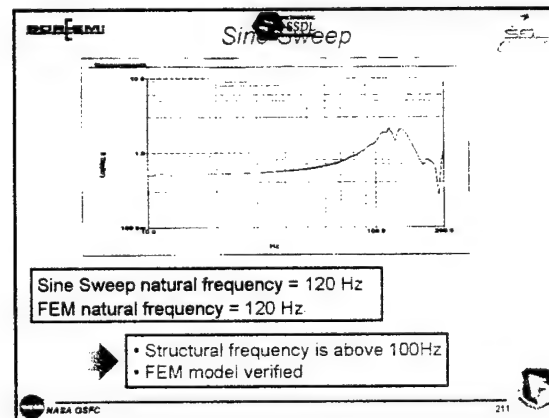
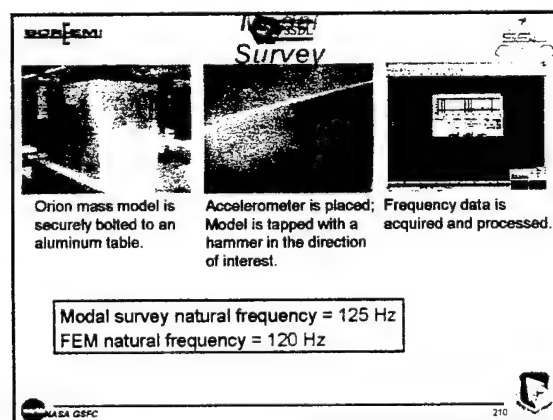
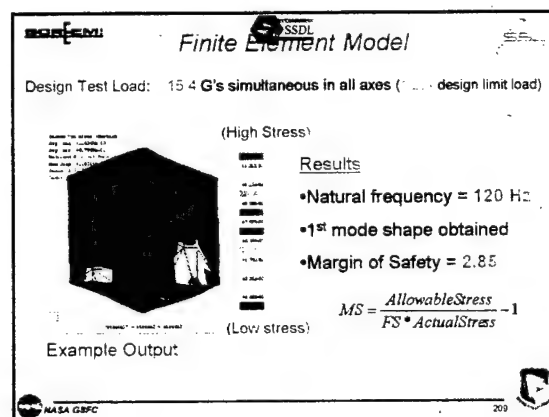
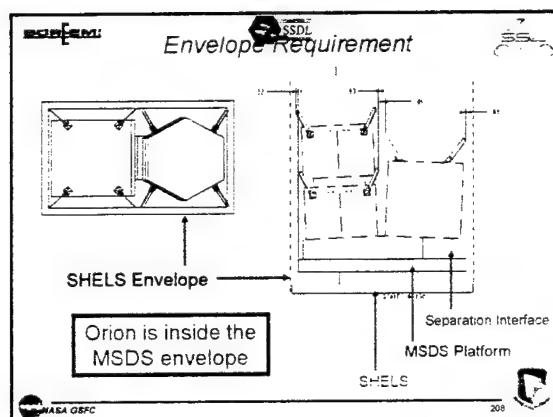
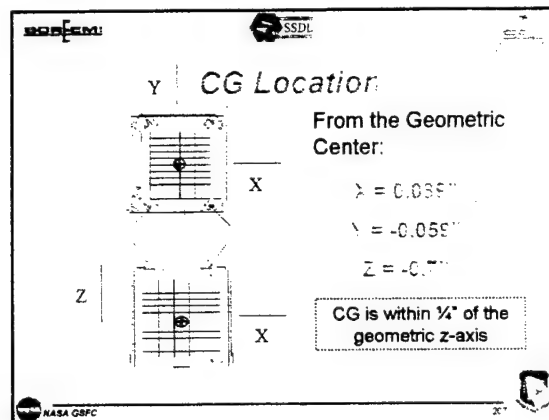
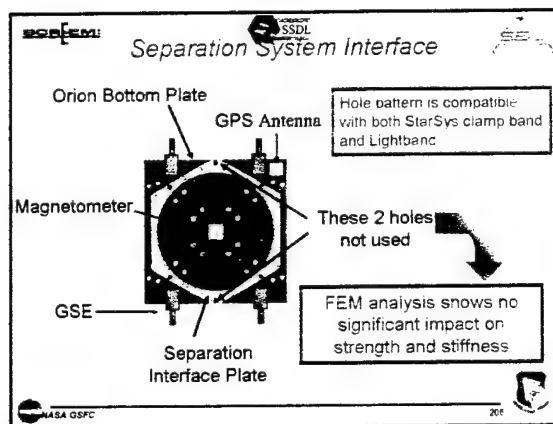
**Propellant Storage & Delivery Unit**

- Function of PSDU:
  - Propellant Storage
  - Supplies propellant to TCORE upon command from TCU
- PSDU Components
  - 10ml Propellant Cartridge
  - DC Motor w/ High-Ratio Gearbox
  - Threaded-Rod / Plunger Pumping Mechanism
- PSDU
  - Self-contained, sealed, battery-operated, medical-grade portable insulin pump
  - Modified to allow pump control by TCU
  - Modified to include a small heater

**CMT Propellant System Rev 1.0**







Fracture Control Overview		
Component	Classification	Compliance
Aluminum honeycomb composite	Fracture critical	<ul style="list-style-type: none"> <li>Material Certification by AL composite supplier</li> <li>Manufacturing consistent with established aerospace practices and done by written procedure</li> <li>Pull testing of insert coupons consistent with flight articles</li> <li>Sine burst testing at assembly level (1.2x design limit load)</li> </ul>

Fracture Control Overview		
Component	Classification	Compliance
6061-T6 Aluminum L Brackets	Low risk; non-fracture critical	<ul style="list-style-type: none"> <li>Table 1 material</li> <li>#3, 4 and 10 fasteners from GSFC</li> <li>#3, #4 fasteners used in high Margin of Safety applications</li> <li>All fasteners will have backoff prevention in the form of locking nuts, locking inserts or lockite</li> <li>All stainless steel inserts will be screened for defects</li> </ul>

Fracture Control Overview		
Component	Classification	Compliance
Battery box	Non fracture critical; low-risk sealed	<ul style="list-style-type: none"> <li>Exempt</li> <li>Aluminum Alloy</li> <li>Proof Tested to 1.5 MDP</li> </ul>
Cold gas propulsion system: low pressure	Non-fracture critical	<ul style="list-style-type: none"> <li>Will be covered later in the presentation</li> </ul>
Cold gas propulsion system: high pressure	Fracture critical	<ul style="list-style-type: none"> <li>Will be covered later in the presentation</li> </ul>

Manufacturing Overview	
Issue	Resolution
Flight Hardware Control	<ul style="list-style-type: none"> <li>Documented Inventory Control</li> <li>Material Certification</li> </ul>
Integration Control	<ul style="list-style-type: none"> <li>Engineering Drawings of all components</li> <li>Isolation of Flight Hardware</li> <li>Manufactured in a Clean Room Environment at Stanford</li> </ul>
Flight Qualification	<ul style="list-style-type: none"> <li>Strength: Sine Burst</li> <li>Natural Frequency: Sine</li> <li>Internal Verification Checklists</li> <li>Vibroacoustic: Random</li> </ul>

Flight Hardware Control	
<ul style="list-style-type: none"> <li>Documented Inventory Control by means of inventory control forms provided by AFRL <ul style="list-style-type: none"> <li>All incoming flight materials will be accounted for in these documents</li> <li>The forms will include purchasing information, quantities, dates, names, incoming inspection and other relevant information</li> </ul> </li> <li>Isolation of Flight Hardware <ul style="list-style-type: none"> <li>All flight hardware will be kept in a clean environment and separate from all other</li> </ul> </li> </ul>	

Integration Control	
<ul style="list-style-type: none"> <li>Procedure Development <ul style="list-style-type: none"> <li>Assembly procedures for all components will be developed during engineering phase and will be used for flight instruction</li> <li>The procedures will include instructions on assembly sequence, fasteners, torque specifications, handling and insert installation</li> </ul> </li> <li>Engineering Drawings <ul style="list-style-type: none"> <li>All machined components have an associated engineering drawing</li> <li>The drawings will be used to accurately manufacture the component to design</li> </ul> </li> </ul>	

**Integration Control**

- Clean Room Environment
  - Flight Model components will be assembled in a clean environment at Stanford
- Internal Verification Checklists
  - A second person will observe and verify that the correct procedure is used to assemble flight components

NASA GSFC 218

**Qualification**

- Pull-testing of sample flight inserts
  - Random samples created for every flight composite panel
  - Samples will be tested and compared to known design strength characteristics
- Flight Strength Qualification by means of sine burst testing
  - Sine burst at 13.75 G's in each direction will be applied to the complete flight model

The flight model must survive without structural failure

NASA GSFC 219

**Flight Qualification**

- Natural frequency verification by sine sweep
  - Infinitely stiff interface will be assumed in this test
  - Accelerometers will be placed to capture the damped natural motion of the structure
  - The natural frequency of the entire structure must be above 100 Hz

NASA GSFC 220

**Requirements Summary**

Issue	Requirement	Compliance
Strength	+/- 11G's all axes simultaneously	Sine Burst Testing, FEM modeling
Natural Frequency	100Hz minimum	Modal Testing, FEM Modeling
Acoustic	Survival of launch vibroacoustic environment	Random Vibration Testing
Mass, CG	Mass limit, CG within 0.25 inch from the geometric	Mass ~35Kg CG within specification
Envelope	Orion envelope within the SHELs envelope.	Orion is well inside the boundary limits
Fracture Control	Prevent structural failure due to flaws	Approved critical components and
Manufacturing	Prevent structural failure due to poor quality	Engineers Model, manufacture by procedure

NASA GSFC 221

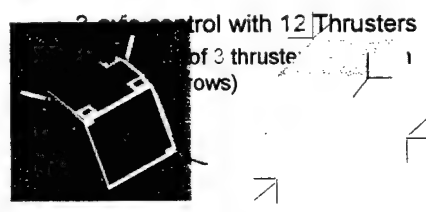
**Propulsion**

NASA GSFC 222

**Design**

A cold-gas propulsion system provides the required 6-DOF control required to meet mission maneuvering objectives

2-axis control with 12 Thrusters  
of 3 thrusters (rows)



NASA GSFC 223

### Design

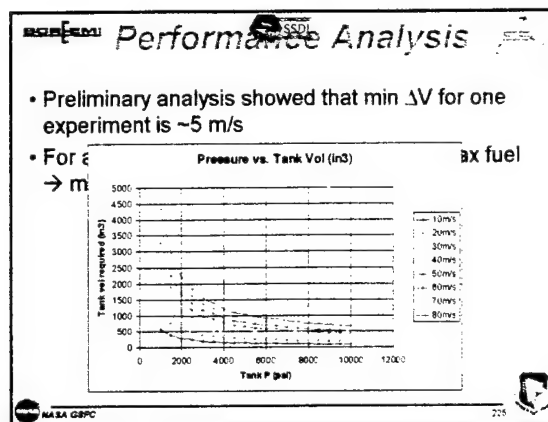
Cold Gas Propulsion:

- Lixten tanks
- GCR regulators
- Anger Scientific valves
- Quick-connect fittings & drain ports

PIC valve control

- Propellant is GN2
- Total Delta-V ~ 25 m/s
- Isp ~ 60 sec. (measured)
- 60 mN thrust per thruster

NASA GSFC 224



### Performance Analysis

- Max P for tank determined by tank limits & NASA requirements
  - $1.5 \times \text{MDP} < \text{Proof (requirement)}$
  - Proof = 7500 psi  $\rightarrow$  MDP < 5000 psi
  - MDP dictated by max Temp (100 deg. C)
  - At 20 deg. C, max Op P = 3500 psi
- Fuel capacity determined by max Op P
  - 0.5 kg per tank (x3)
  - 1.5 kg GN2 total

NASA GSFC 226

### Parameters

Maximum delta V within mass/volume budget ~26 m/s

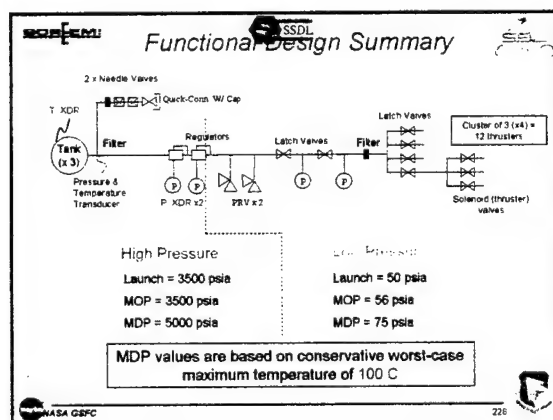
- 3 cylindrical tanks
- High pressure (3,500 psia)
- Fuel : GN2

Budget constraints

- COTS parts
- Miniature valves and fittings
- In-house parts (low pressure side)

Thruster manifold

NASA GSFC 227



### Mass Budget

Component	Mass (g)	amount	Total (kg)
Tank	1359	3	4.077
Regulator	325	2	0.65
Line Filters	274	2	0.548
Thruster Valve	24	12	0.288
Latching Valve	86	6	0.516
P. XDR (regs)	8	3	0.024
P. XDR (HP/LP)	10	3	0.03
Temp. Sensor	2	5	0.01
Plumbing	2000	1	2
Quick Connect	100	1	0.1
PRV	200	2	0.4
Manual Valves	500	2	1
Holders	75	3	0.225
Manifold	56	4	0.224
Nozzles	5	12	0.06
Electronics	1000	1	1
Fuel	1.5	1	0.0015
			11.2

NASA GSFC 229

**Primary Materials List**

- Main Material
  - Stainless Steel
  - Aluminum
- Elastomers, Seals, O-rings
  - PEEK
  - Viton
  - Teflon
  - Tefzel

NASA GSFC 230

**Components**

3 Cylindrical Tanks (Vendor: Luxfer Inc.)

- Carbon fiber wrapped
- Initial fill pressure 3500 psig
- Proof : 7500 psig, Burst : 1530X
- Fuel: GN2

NASA GSFC 231

**Components**

Service Port

- 2 manually operated needle valves
- 2-micron filter
- MOP rating of 6000 psig
- Proof : 12000 psig, Burst : 24000 psig
- 1 quick-connect (self-sealing)
- MOP rating of 10 ksig
- Proof : 20 ksig, Burst : 40 ksig
- Provide 2 fault tolerant mechanical inhibit from inadvertent release of GN2

Example Quick-Connect

NASA GSFC 232

**Components**

Regulators (vendor: GoRegulators)

- 2 in series prevent high pressure from reaching low pressure side of system
- MOP rating of 6000 psig
- Proof : 12000 psig, Burst : 24000 psig
- Monitored using pressure transducer
- Tamper-proof handles (not shown)

NASA GSFC 233

**Components**

Pressure Relief Valves (vendor: Swagelok)

- Two in parallel prevent high pressure from over-pressurizing low pressure side of system
- MOP rating of 6000 psig
- Proof : 12000 psig, Burst : 24000 psig
- Setting preserved by lockwire
- Two PRVs required to relieve high-pressure "free-flow"

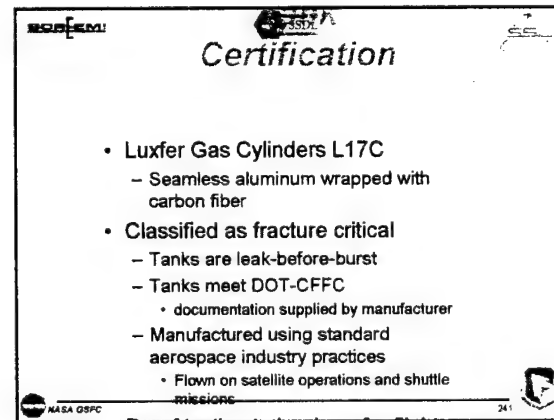
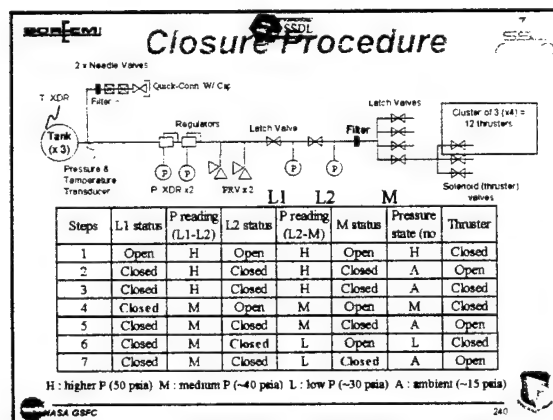
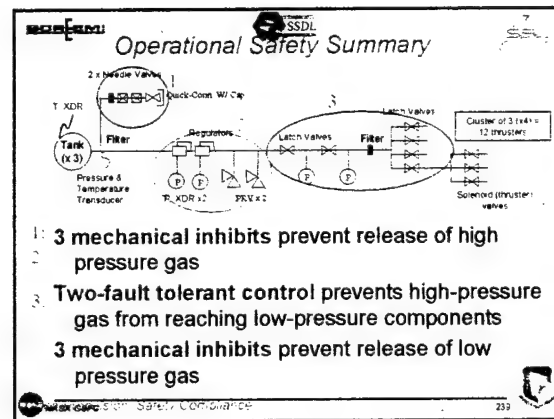
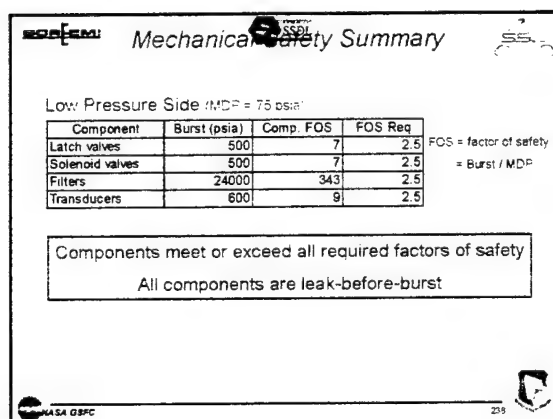
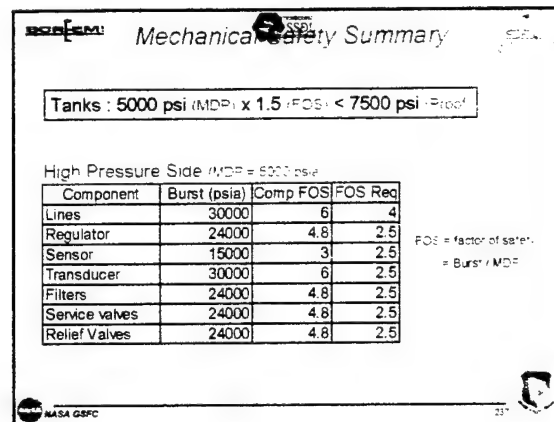
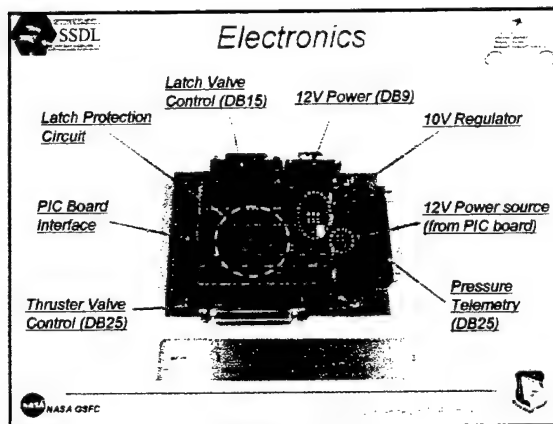
NASA GSFC 234

**Components**

Latch and Solenoid Valves (Angar Scientific)

- Electronically operated
- Provide 2 fault tolerant mechanical inhibit from inadvertent firing or leak
- MOP rating of 100 psig
- Proof : 250 psig, Burst : 500 psig
- 4 electrical inhibits prevent inadvertent operation

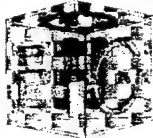

NASA GSFC 235



## Tank Thermal Analysis

Analysis results:

- Starting condition of 100 C
- Worst-case heating (sun on top panel, earth on bottom)
- Radiation heat transfer only from propellant tanks

LM ATC IDEAS/TMG Model
Results after 20 minutes deployment

NASA GSFC

## Manufacturing

- Assembly done in clean environment
  - Class 10000 clean room for construction
  - Parts stored in "clean box" (inside clean room)
- Assembly Plan
  - Assemble main propulsion building blocks in clean room
    - Thruster clusters : thruster valves, fittings, manifold, and nozzles
    - Regulator cluster : regulators, pressure transducers on "baseplate"
    - Latch valve clusters : fittings, pressure transducers on "baseplate"
    - Service port : manual valves, fittings, and quick-connect
  - Integrate into structure in clean room
    - Tanks are placed and connected to service port
    - Integration of "baseplates" onto structure

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## Performance Testing

- Nozzle tested using vacuum chamber
  - Each flight nozzle is fired directly upward; firing duration is minimized to reduce pressure effect on test apparatus
  - Spring/mass system records thrust
  - Mass flow recorded, Isp calculated
- Current results closely match the theoretical values
- All flight nozzles tested to ensure consistent quality
- All electronic systems (valves, sensors, and PIC) checked for correct operation

Thrusters will be actuated randomly to check for

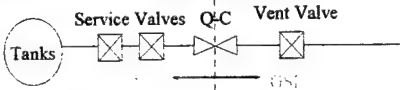
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## Testing

- Proof Testing required for flight
  - Tanks are qualified as per MIL-STD-1522A "Path C" (reference : Figure 2, p. 28)
  - Hydrostatic testing
    - System cycled twice at 1.5 x MOP
  - Visual inspection, leak test
- Functional
  - Valve actuation
  - Leak test

NASA GSFC

## Ground Ops Procedures



- Filling Prop system
  - Mate Quick-Connect
  - Open service valves
  - Start GN2 flow
  - Fill tanks
  - Close both service valves
  - Stop GN2 flow
  - Open vent valve
  - Disconnect Q-C

NASA GSFC

## Requirements Summary

Issue	Requirement	Compliance
Attitude control	Perform required maneuver	Test functions of 12 thrusters
Attitude control	3-axis control	Test 12 thrusters required for 3-axis
Fracture control	All components meet and exceed safety factor	Some components that exceed FOS Parts are Leak
Inhibits	Mechanical inhibits/controls and	Before Burn verify required inhibits
Vibration/Load	Electrical inhibits vibroacoustic environment	Shake Test

NASA GSFC Summary

**Auxiliary Control**

NASA GSFC

**Requirements**

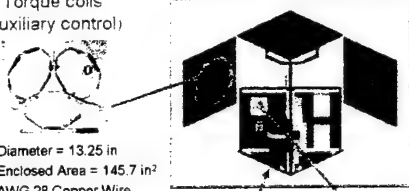
Orion main ADOS requires phase lock control between propulsion and GPS system without a GPS signal, an auxiliary method of control is required.

- **Primary Function**
  - Detumble Orion from initial tip-off after deployment or satellite reset events
    - Total spin rate less than 0.7 rad/min (0.67 deg/sec)
  - Overcome any environmental disturbance torques (primarily aerodynamic disturbances)

NASA GSFC

**Design**

Torque coils (auxiliary control)



- Diameter = 13.25 in
- Enclosed Area = 145.7 in<sup>2</sup>
- AWG 28 Copper Wire
  - 550 Turns, 137 Ohms
- Mass = 700 g/coil
- Nominal Current = 100 mA
- Dipole Moment = 5.1 A-m<sup>2</sup>
- B-field Strength = 1.6 Gauss

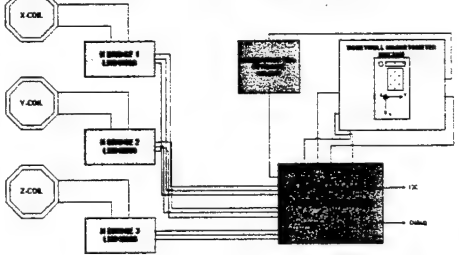
PIC microcontroller runs control algorithm

under bottom pane:

- Honeywell HMC2003 magnetometer
- Dipole moment ~5 Am<sup>2</sup>

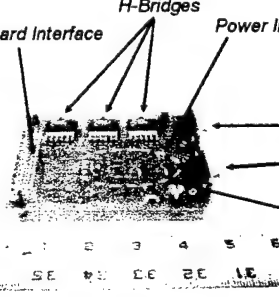
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**Functional Diagram**



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**Electronics Board**



PIC Board Interface

H-Bridges

Power Interface (PIC board)

DB9 connectors

Torquer Coils

Magnetometer

Set/Reset Circuit

NASA GSFC

**LMD18200 H-bridge**

National Semiconductor LMD18200 (1 per coil)

- Operating Voltage: +12V to +55V
- Operating temperature: -40 to +125 C
- 3A maximum continuous output capability (6A peak output)
- 3 logic inputs per H-bridge


Logic inputs will be used to control the torquer coils

NASA GSFC

**Honeywell Magnetometer**

- 3-axis magnetic field measurements
- Magneto-resistive permalloy sensor
- 40uGauss resolution
- Field range: -2 to +2 Gauss
- Supply voltage: +5 to +15V
- Maximum supply current: 20mA
- Operating temperature: -55 to +125 C

Secure Reset Circuit:  
 • Eliminates effect of past magnetic history  
 • Eliminates size (momentarily flip polarity)  
 • Higher resolution and maximize sensitivity  
 • Provides for temperature drifts



**Materials Summary**

**Coil Assembly**  
 Aluminum U-channel AL-6061  
 Insulated Magnet Wire C11100 (AWG28) - NEMA 1000 MW-73/35 UL  
 Epoxy: Stycast 2850FT with Catalyst 9

**Electronics - PIC Board**  
 Board: FR4  
 Copper  
 Surface Mount ICs  
 DB9 Connectors: Mil-c-24308

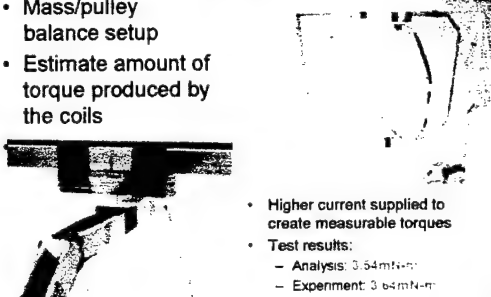
**Electronics - Subsystem Control Board**  
 Board: FR4  
 Copper  
 Surface Mount ICs  
 DB9 Connectors: Mil-c-24308  
 H-Bridge  
 Magnetometer

**Mass Budget**

Major Component	Quantity	Mass per Item (g)	Total Mass (g)
Wire Coil	3	666	1998
Epoxy	3	100	300
PIC daughter board	1	65	65
PIC mother board	1	100	100
Magnetometer	1	10	10
<b>Total Subsystem</b>			<b>2473</b>

**Coil Performance**

- Mass/pulley balance setup
- Estimate amount of torque produced by the coils



- Higher current supplied to create measurable torques
- Test results:
  - Analysis: 0.54mN-m
  - Experiment: 0.64mN-m

**Control Law**

Minus K-Bdot Law: Earth's Magnetic Field

$$\mathbf{M} = -k(\mathbf{dB}/dt)$$

Control Gain

Time rate of change of the magnetic field in the body frame

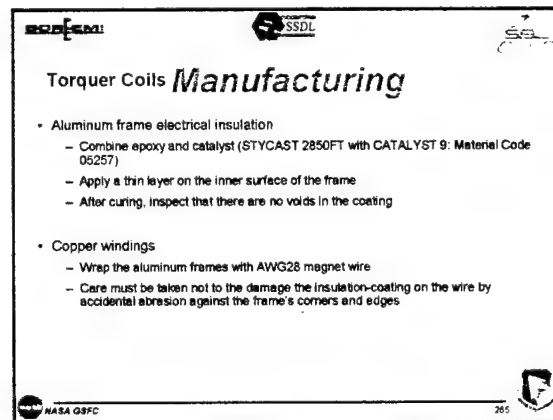
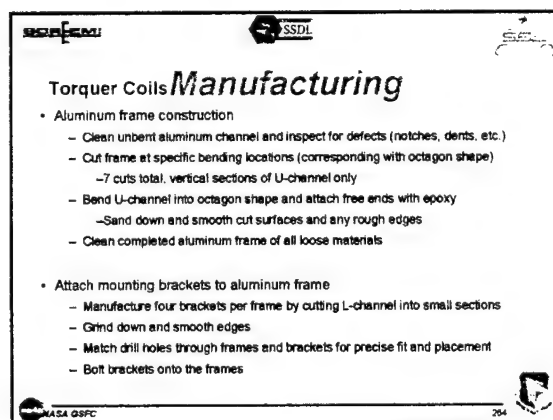
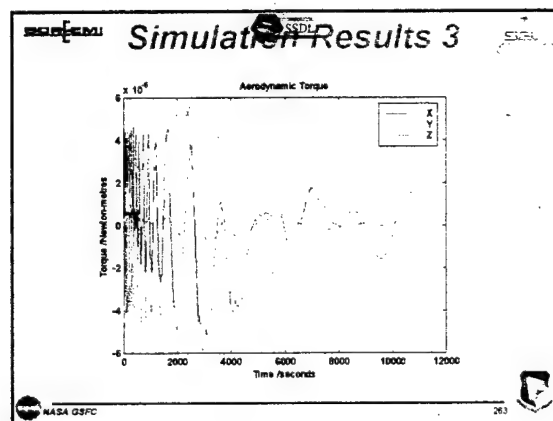
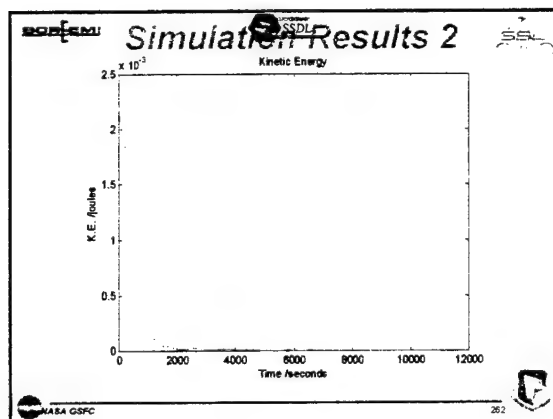
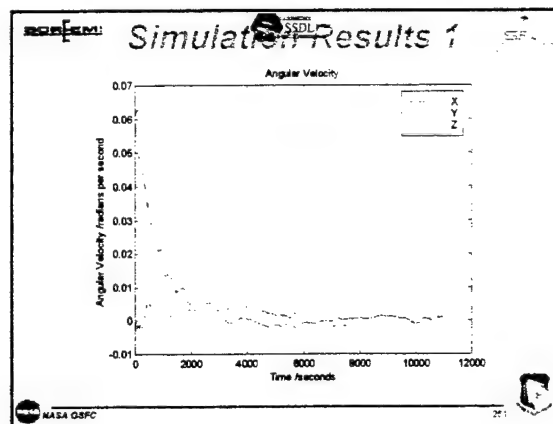
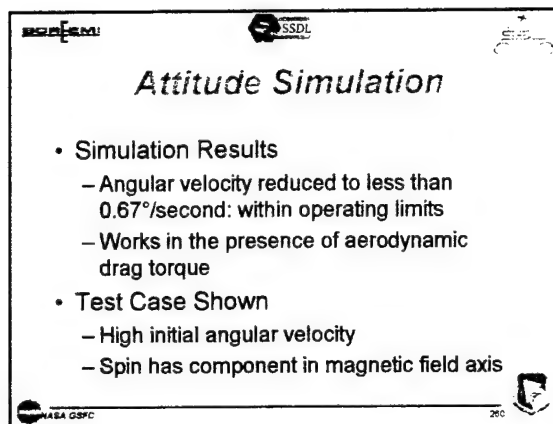
Control torque  $\mathbf{T} = \mathbf{M} \times \mathbf{B}$

- Coils can either can be ON (in two directions) or OFF
- Vary the torque produced by the coils in a "time averaged" sense

**Attitude Simulation**

- Integrated Attitude Simulation
  - Full nonlinear attitude simulation
  - Works in conjunction with our orbit and station-keeping simulations
  - Includes aerodynamic drag and residual dipole disturbances
  - Verified with several known test cases
- Realistic testing of controllers

Torquer coil & magnetometers



**Control Board Manufacturing**

- The Printed Circuit Board (PCB) of the Control Board will be manufactured by Advanced Circuits, Inc. according to our design
- Populating the PCB
  - Each component will be soldered in place one-by-one in an orderly fashion following the board design layout

**Magnetometer Board**

- The Magnetometer PCB will be manufactured by Advanced Circuits, Inc. according to our design
- Populating the PCB
  - The magnetic sensor will be soldered onto the board and the connections will be visually and electronically inspected.

NASA GSFC 265

**Testing & Integration**

**Torque Coils**

- During the coil winding process check for electrical shorts between wires and frame every 100 turns
  - Ensure even spacing of windings
- Measure the B-field generated by the coils using the magnetometer
  - Place magnetometer in the center of the coil and gather data
  - Compare with design value
- Interface with the Control Board and test each coil
  - Monitor the H-bridge telemetry data (current output) and verify proper operation of each coil
- Mount each coil on the interior of Orion's panels
  - Test for electrical shorts between the coil assembly and panels
  - Make sure coils are properly fastened in place

NASA GSFC 266

**Testing & Integration**

**Control Board**

- Connection continuity tests during board populating procedure
- Board circuitry testing of:
  - Magnetometer Set/Reset circuit
    - Visually confirm proper pulse signals using an oscilloscope
  - Magnetometer ON/OFF control circuit
  - H-bridge operation
- Interface with PIC board and validate board functionality
  - PIC code operations
- Integrate PIC board/Control Board with Power Bus
  - Confirm that enough power is supplied for full subsystem operations

NASA GSFC 268

**Requirements Summary**

Issue	Requirement	Compliance
Torque	Provide enough to overcome any anticipated disturbance torques and detumble Orion	Measure generated magnetic field and compare with EM data
Control Algorithm	Vary actuation time and direction of dipole moment depending on measured B-field	EM PIC code development and testing
Control Algorithm	Detumble Orion down to 0.7 rad/sec	Simulation results
Maximum B-field	Must be below strength specified in the Shuttle Orbiter/Cargo Standard Interfaces Document ICD 2-19001 Rev. L (11/95)	Current design, as measured using a magnetometer is below 170 dBpT at 140 Hz

NASA GSFC 269

**Orion Power**

NASA GSFC 270

**Design**

**Solar cells**

- SpectroLab 2J-GaAs
  - 20% cell efficiency
  - 6-cell strings (16.5V, 294mA per)
  - Bonded to panels over insulating substrate
  - 26W peak supply to bus
  - 16W time-average supply to bus

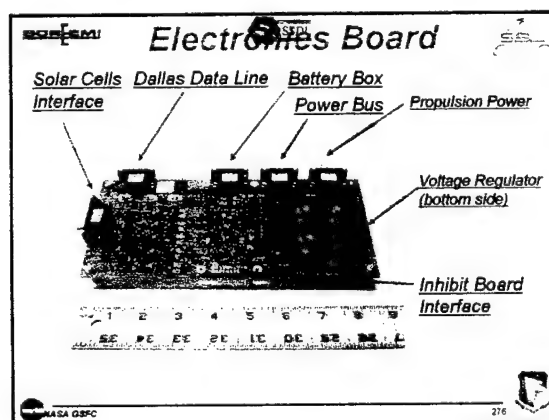
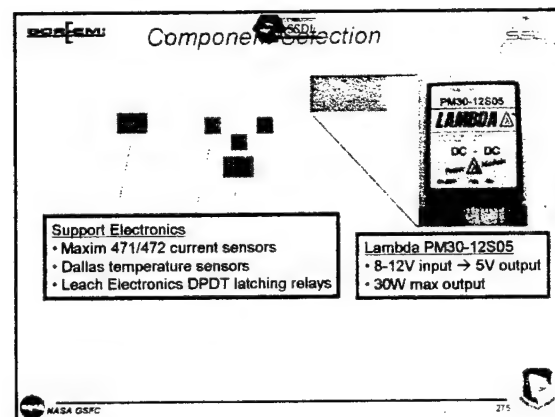
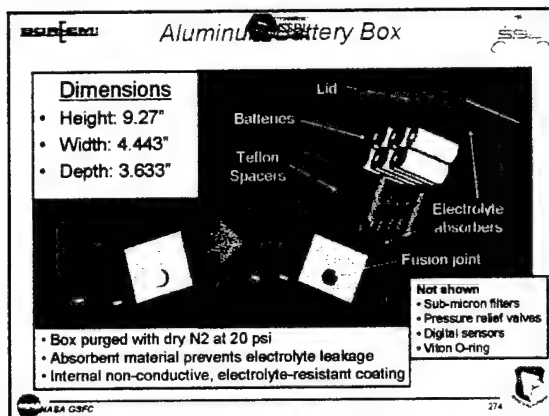
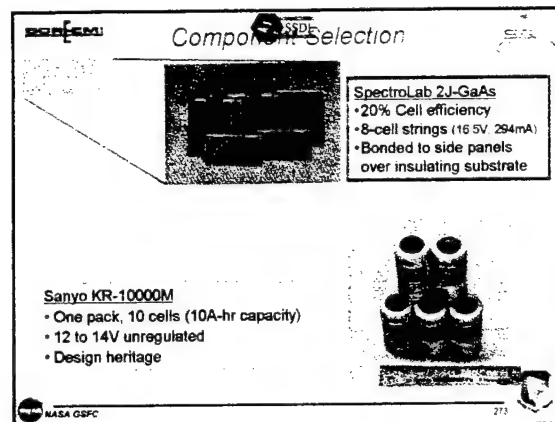
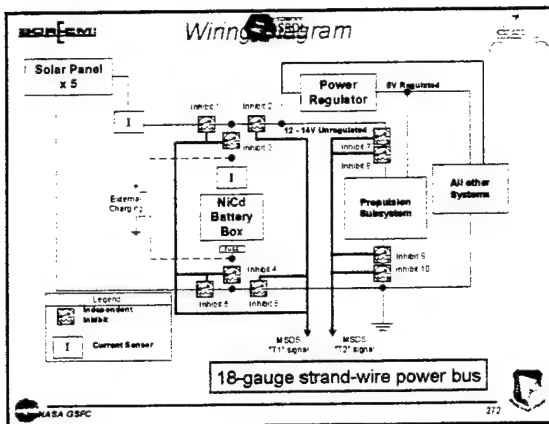
**Sanyo KR-10000M**

- 10A-hr capacity
- 12 - 14V unregulated
- Design heritage

**Support Electronics**

- Lambda 5V regulator
- Maxim 4711472 current sensors
- Dallas temperature sensors

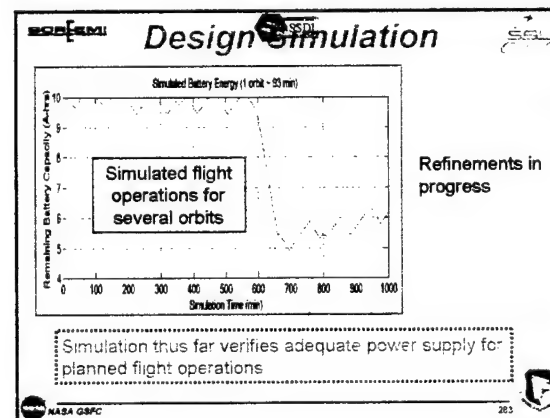
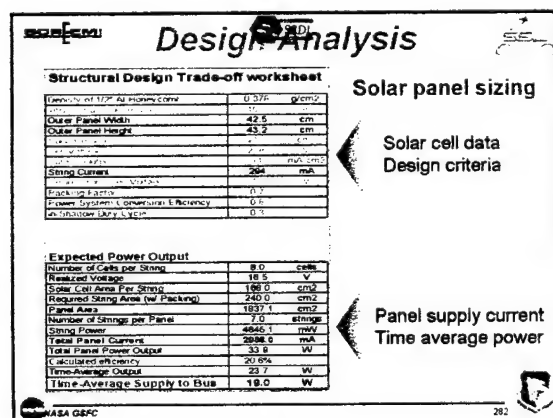
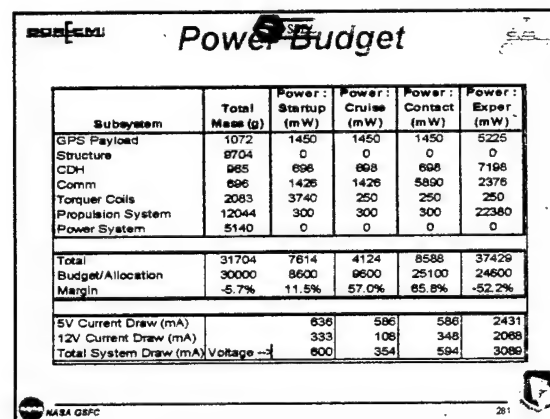
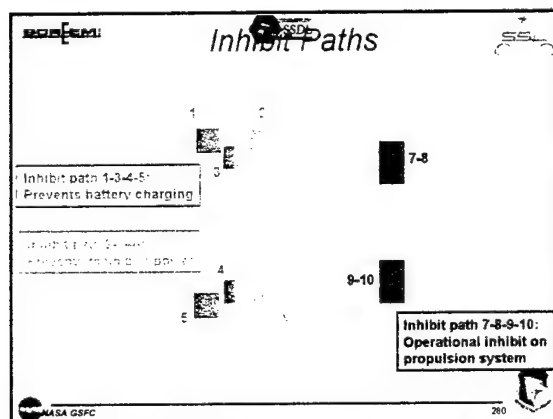
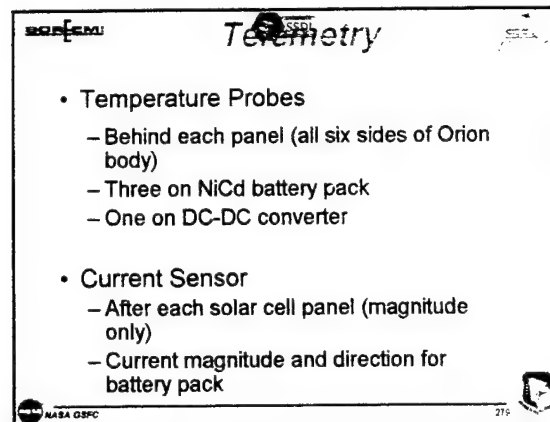
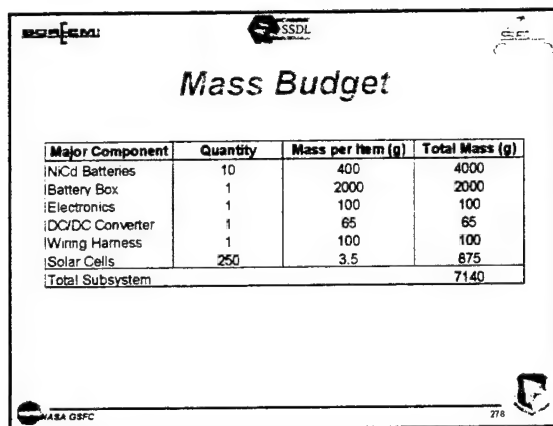
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### Materials Summary

<b>Power Bus</b>
Electrical Wiring
DB9, DB15, DB25 Connectors: Mil-c-24306
<b>Electronics - Printed Circuit Board</b>
Board: FR4
Copper
Surface Mount ICs
DB9, DB15 Connectors: Mil-c-24306
<b>Batteries</b>
Nickel Cadmium
<b>Battery Box</b>
Aluminum 6061
Fiberglass
Teflon
<b>Solar Cells</b>
Gallium Arsenide
Glass

NASA GSFC 277



**Spacecraft Test Port Interface**

- Provides terminals to charge batteries after integration
- Provides inhibit bypass, verification, and reset during test and integration
- Allows external the spacecraft **DB Connector Required**
- DB25 Connector
- Allows final inhibit verification
- 10 inhibits with 2 pins each for latching + 1 common ground pin = 21 pins
- NiCd battery pack charging = 2 pins
- Total number of pins = 23 pins

NASA GSFC 284

**Manufacturing**

**Power Board & Inhibits Board**

- The Printed Circuit Boards (PCB) for the Electric Power Subsystem will be manufactured by Advanced Circuits, Inc. according to our design
- Populating the PCB
  - Each component will be soldered in place one-by-one in an orderly fashion following the board design layout

**Battery Box**

- Machine aluminum box to design dimensions
- Attach pressure relief valve to completed box
- Install fiberglass and Teflon spacer material
- Place NiCd battery pack into box and attach DB9 connector for interfacing with the electronics board

NASA GSFC 285

**Testing & Integration**

**Power Board**

- Connection continuity tests during board population procedure
- Board circuitry testing of:
  - Voltage regulator operation: measure outputs vs. inputs
  - Current sensor outputs: verify with voltmeter measurements
  - Dallas AD converter outputs: verify with voltmeter measurements
  - Simulate inhibit closing by connecting header pins
  - DB9 connections and pin outs

**Inhibits Board**

- Connection continuity tests during board population procedure
- Manually open and close inhibits and perform continuity tests for each inhibit
  - Test using the header pins used to interface with the Power Board
  - Test using the STPI DB25 connector
  - Test using the MSDS DB15 connectors (for T1 and T2)

NASA GSFC 286

**Testing & Integration**

**Power & Inhibits Boards**

- Integrate the Inhibits Board with the Power Board
  - Verify header pin connection

**Battery Box**

- Measure physical dimensions and confirm size
- Verify mounting hole locations and integrate with Orion structure
- Box interior:
  - Proper placement of fiberglass material
  - Proper seal at relief valve-to-box interface
  - Proper seal of completed battery box
- Verify mounting hole locations and integrate with Orion structure
- Integrate with Power Board
  - test for voltages (unregulated 14V and regulated 5V)

NASA GSFC 287

**Testing & Integration**

**Solar Cells**

- Connect with electronics board
  - Verify proper connections
  - Observe outputs on current sensors
  - Check for the unregulated 14V and regulated 5V lines

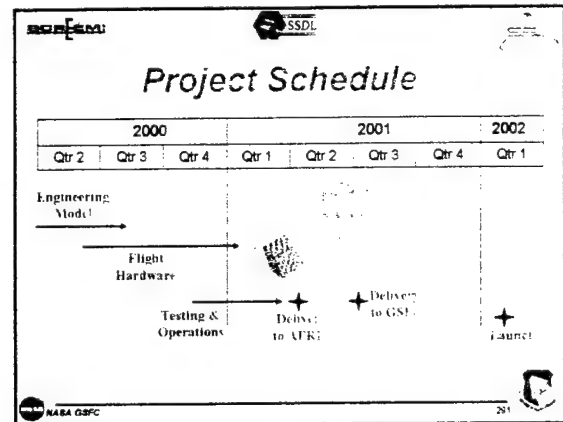
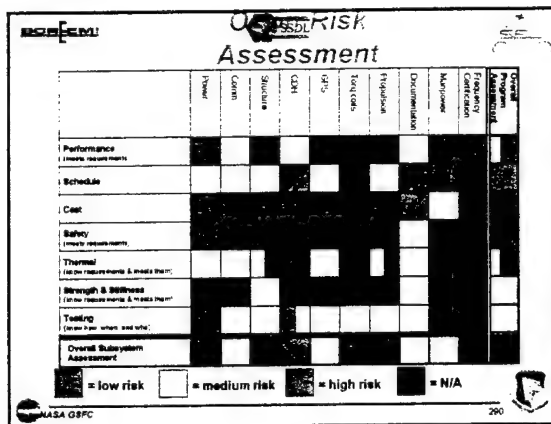
**Full Subsystem**

- Test inhibits through the STPI
  - Open and close inhibits
  - Check for continuity across each inhibit
  - Check for the unregulated 14V and regulated 5V lines
  - Check that the Propulsion Subsystem is inhibited per design
- Test inhibits through the MSDS connectors
- Connect various subsystems individually and observe operation of each subsystem
- Full system integration and observe operation of Orion

NASA GSFC 288

**Orion Program Risk Assessment**

NASA GSFC 289



## Nanosat One Critical Design Review

Principal Investigators:  
 Prof. Jonathan How  
 Prof. Christopher Kitts  
 Prof. Robert Twiggs

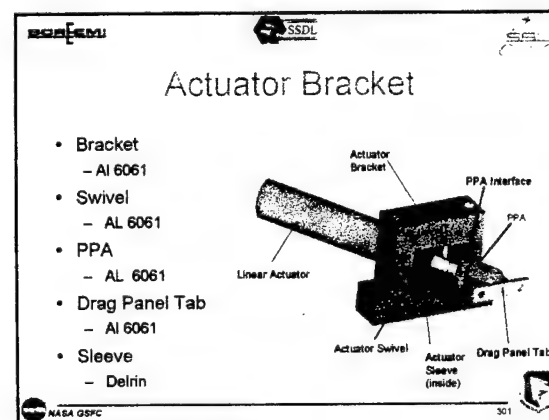
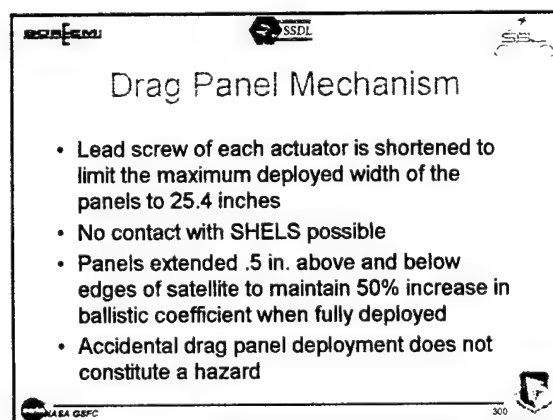
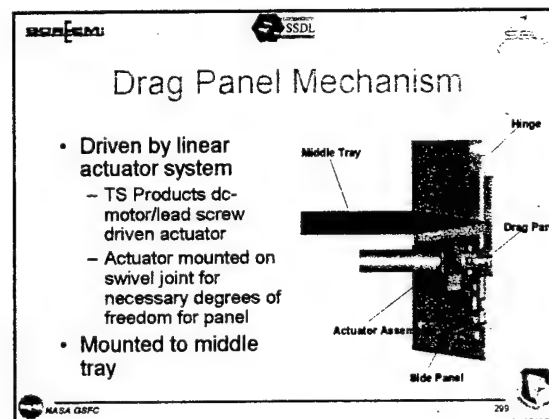
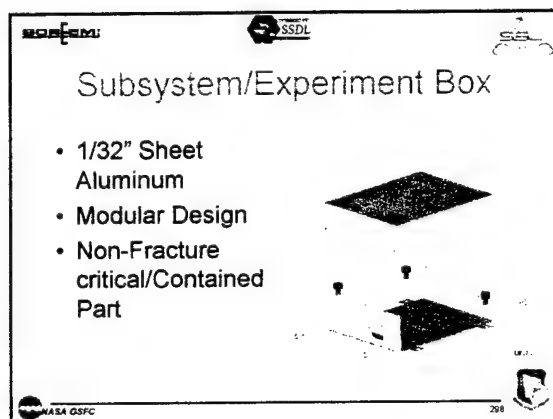
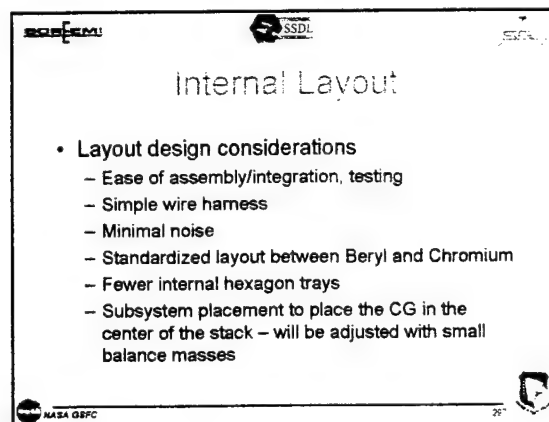
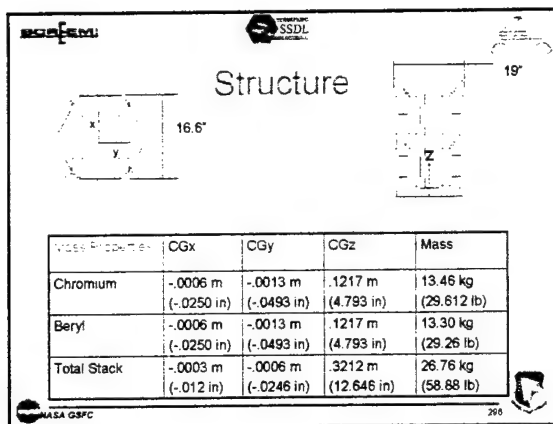
## Emerald Structures and Mechanisms Subsystem

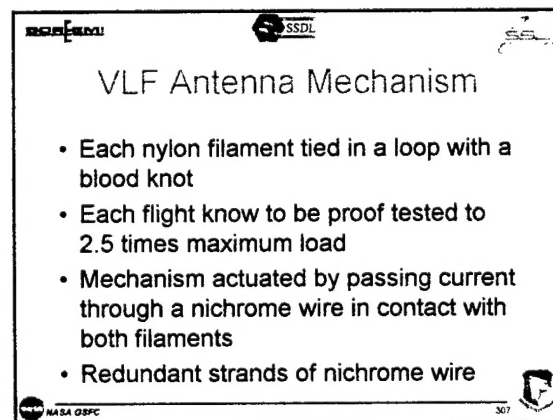
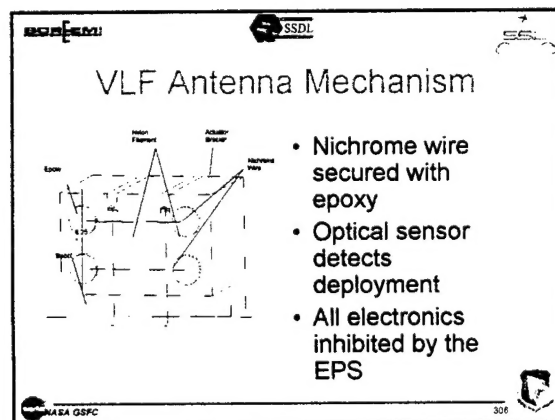
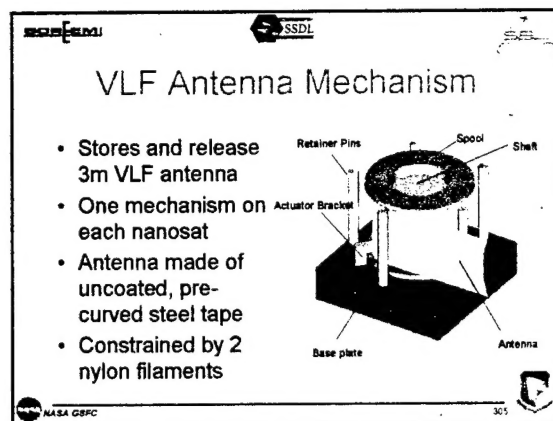
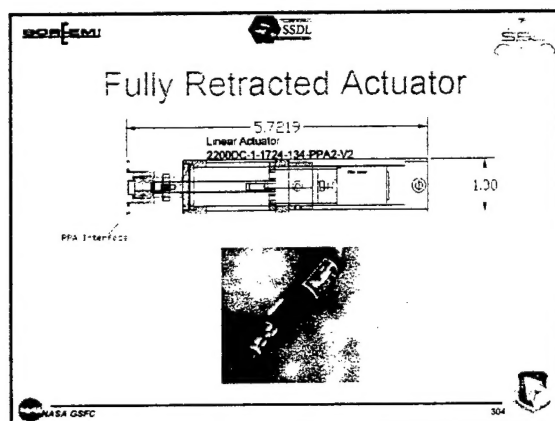
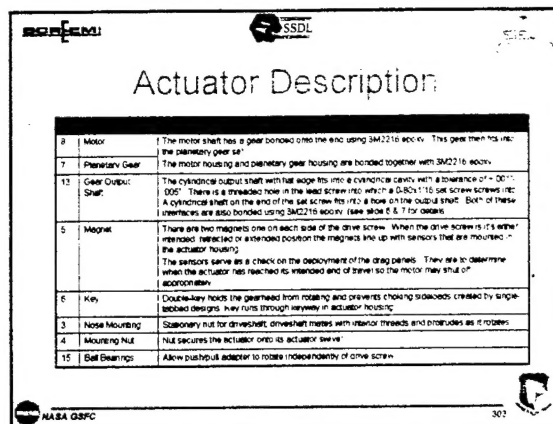
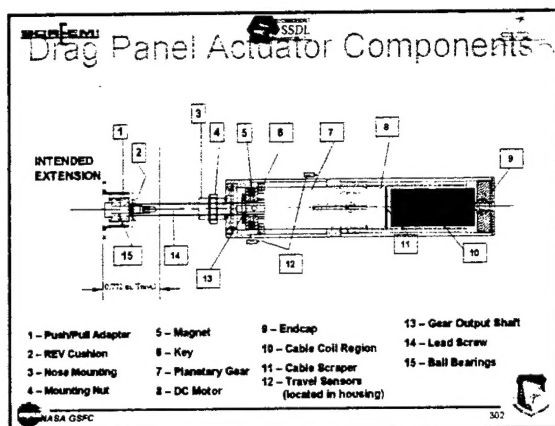
### Design Summary

- Structure
  - Heritage SSDL design modified to meet 100Hz natural frequency requirements
- 3 Major mechanisms
  - Drag panel actuation mechanism
  - VLF antenna deployment and retention mechanism
  - Lightband intersatellite separation system
- Lightband designed by Planetary Systems

### Structural Design

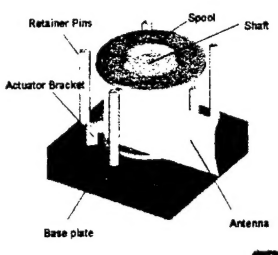
- Heritage SSDL Design
- Aluminum Honeycomb Hex Plates & Side Panels
  - 5052 Grade Aluminum (face skins)
  - 3003 Grade Aluminum (core)
- Longerons
  - 303 Stainless Steel 10-32 All-Thread
- Spacers and L-brackets
  - 6061T6 Aluminum
- Prototype structure with mass simulators tested to 11G's in random vibration with no damage





## Materials

- VLF mechanism
  - Spool – Al 6061
  - Shaft – Delrin
  - Retainer Pins – Delrin
  - Actuator Bracket – Delrin
  - Antenna – Spring Steel Stanley Tape Measure



SSDL

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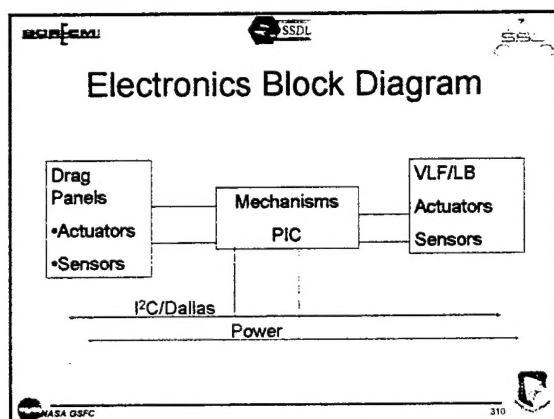
## Supporting Electronics

- Drag Panel Sensors
  - Hall Effect: Fully Deployed
  - Hall Effect: Fully Retracted
  - Redundancy: Current Sensor
- Lightband/VLF Sensors
  - Micro-switches: Deployment Confirmation
  - Optical Sensor: Deployment Confirmation
  - Redundancy: Extra micro-switch on LB

SSDL

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## Fracture Control Classification

Component	Classification
AL Honeycomb Composite	Fracture critical composite/bonded structure
Linear Actuator	Fracture critical component
VLF nylon retention system	Fracture critical composite/bonded structure
Fasteners, L-brackets, Longerons, Spacers	Non Fracture Critical Low Risk

SSDL

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## Structural Design Analysis

- FEA to determine structural design
  - Ideas v.7 FEM package
- Approach
  - Match previous vib tests of engineering model
  - Update satellite connection to model Lightband
  - Test various design changes to increase frequency

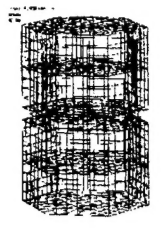
SSDL

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## Structural Analysis

- Building block solutions to verify with test
  - Fix middle plate to side panels with L-brackets
  - Add additional longeron(s)
  - Tie side panels together with angle bracket



SSDL

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## Design Analysis

- Strength analysis of drag panel in deployed configuration
- Test verified analysis to show adequate strength margin in nylon line in VLF mechanism
- Thermal IDEAS TMG model for on-orbit analysis
- Strength analysis and test of insert pullouts

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## Thermal Controls

- Passive thermal control
  - Insulation blankets
  - Thermal tape
  - Cooling through radiation from body panels
  - Heating through power dissipation
- IDEAS thermal model for analysis

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## Temperature Limits

Acceptance Levels for Operation

Sub-System	Low Temp. (C)	High Temp. (C)
GPS	-40	85
CMT	0	50
Distributed Computing	0	50
VLF Experiment	-25	85
COMM - Receivers	10	80
COMM - Transmitters	10	80
CALDH - SOFC	0	85
CALDH - Modem	-20	80
Batteries	-30	80


Qualification Levels

Sub-System	Low Temp. (C)	High Temp. (C)
GPS	-40	85
CMT	-20	85
Distributed Computing	-40	85
VLF Experiment	-40	85
COMM - Receivers	-40	85
COMM - Transmitters	-40	85
CALDH - SOFC	-40	85
CALDH - Modem	-40	85
Batteries	-30	50

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## Thermal Analysis

- FEM results
  - Free floating nanosat snapshot
  - Temperatures on orbit do not exceed limits



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## Manufacture

- Verifiable materials: certifications of compliance
- Instruments to be calibrated prior to use
- Manufacturing to be done under strict configuration management
  - Part drawings accompanied by manufacturing procedure and guidelines
  - Progress checks along manufacturing procedure to be done by second party
  - Final part verified by systems engineer

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## Assembly

- All fasteners supplied by GSFC
- Assemble according to procedure
- Assemble and store in clean environment
- Controlled access to flight hardware

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**Test**

- Stack Level
  - Random Vibration
  - Frequency Characterization
  - Sine Burst
  - Thermal Vac Test
- Component Level
  - Proof test every flight knot for VLF mechanism to 2.5 times calculated dynamic load
- Fracture Critical Components
  - Proof Test to no less than 120% of limit load
  - Procedures to prevent damage from handling or final assembly
  - Manufacturer Certification
  - Create Test Articles

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**Ground Operations**

- Drag panels may be tested on the ground via the STPI or by being commanded through an air link
- No other ground operations

NASA GSFC 321

**Requirements Fulfillment**

- AFRL Requirements
  - Analysis shows that the structure will exceed 100 Hz in natural frequency
  - All separation system hole patterns conform to Lightband standard
  - RFDW approved for antenna exceeding the MSDS envelope
- Safety Requirements
  - VLF and drag panel mechanisms approved

NASA GSFC 322

**Emerald Envelope**

NASA GSFC 323

**Emerald Envelope**

SHELS envelope

Antennas fit within the SHELS envelope

MSDS center plane  $x = 0$

These dimensions approved by AFRL via RFDW

$d1 = 0.342"$   
 $d2 = 0.962"$   
 $d3 = 1.06"$   
 $d4 = 0.45"$

NASA GSFC 324

**Emerald Envelope**

- Completely deployed drag panels fit within SHELS envelope

Static SHELS envelope

NASA GSFC 325